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Nitrogen utilization and capture by winter triticale

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Chapter 1: General Introduction

Winter triticale (X*Triticosecale* Wittmack) has been suggested as a crop to enable Iowa farmers to diversify their current corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) cropping systems. Triticale can be used as a cover crop for the winter months when fields are normally bare, grazed or ensiled to provide additional forage for cattle, or grown for grain that can be an excellent feed source for swine and cattle (McCloy et al., 1971; Hale et al., 1985) because of its high protein and lysine content (Hill and Utley, 1989; Myer et al., 1989; Brand et al., 1995). Recent research with rye (*Secale cerale* L.) suggests triticale may recover N left in the soil from previous crops, thus decreasing nitrate leaching during the fall, winter and early spring months (Ruffo et al., 2004). By decreasing nitrate leaching, winter triticale may prevent excess amounts of NO_3-N from being lost to surface and ground water (Kanwar et al., 1996; Strock et al., 2004; Kocyigit, 2004). By growing triticale to maturity, farmers can harvest not only the grain but also the straw that can be used for bedding or perhaps for bioenergy or other bio-based products.

Before a crop or livestock producer will adopt a new crop, several basic economic and production questions must be answered. The specific questions and their relative importance will generally reflect the producer's interests, abilities, and management skills (Katsvairo et al., 2000). Increasingly, producers must assess the environmental consequences of their practices due to societal concerns about non-point source pollution from agriculture. This thesis examines three important questions that must be answered to produce triticale economically while maximizing its ability to capture residual N from the soil. 1) What is the optimum soil N status for triticale production in Iowa? 2) What are the relationships between soil N status and soil quality indicators, especially NO_3-N? and 3)

What is the optimum soil N status and soil quality when triticale is grown after corn or soybean crops?

Thesis Organization

This thesis is organized for inclusion of a manuscript to be submitted as a journal paper. Chapter 1 provides a general introduction, which is followed by a literature review that discusses placing triticale in the cropping system, N management, and soil quality (Chapter 2). Chapter 3 is a paper on winter triticale N uptake and use to be submitted to a journal. Chapter 4 summarizes the results of this research in its entirety and includes overall conclusions drawn from the research. An Appendix contains ANOVA tables and citations of the literature used in the general introduction (Chapter 1), the literature review (Chapter 2), and the literature cited in each journal paper.

Chapter 2: Literature Review

Triticale's Potential Role in Iowa Cropping Systems

Triticale can be used in many different ways to diversify Iowa crop rotations. It can be used as a cover crop, for supplemental forage (grazed or ensiled), as a grain crop that has good feed qualities and as a source of high quality straw that can be used for bedding or as a potential bioenergy feedstock. With interest in bioenergy increasing, the straw could add substantial value to the crop production system and provide the increased economic incentive Iowa farmers may need to diversity their current farming operations. By introducing triticale as a third crop, the time between planting of successive corn and soybean crops will be lengthened possibly resulting in greater yields and reduced pesticide use.

Before Iowa farmers will begin to use triticale as a cover crop or to diversify their crop rotations there are many questions needing answers. Previous research on winter triticale in Iowa examined how planting date affected winter triticale grain yield, dry matter production, and N accumulation (Schwarte et al., 2004). Planting in mid- to late-September maximized triticale grain and forage yields. Above ground dry matter ranged from 52 to 161 kg ha^{-1} N removed depending on season, location, and planting date. In one of two seasons, N accumulation was 37% greater for mid-September planted triticale than mid-October planting. There was no difference in N accumulation among planting dates during the other season. Triticale was not tested against other species, but it appeared to be efficient in capturing N during the early spring when N is most likely to leach because of high rainfall. More than 50% of triticale N uptake occurred by mid-May and nearly 75% of N uptake had occurred by late May.

Triticale as a Cover Crop

The use of cover crops can reduce nitrate loss to subsurface drainage (Strock et al., 2004) and prevent degradation of water quality by recovering N left in the soil by previous crops (Kessavalou and Walters, 1999). The N captured by the cover crop can be returned to the soil when it matures or is killed, thus retaining N in the soil profile for the next crop (Kristensen and Thorup-Kirstensen, 2004). Cover crops can also reduce soil erosion by providing surface cover and they may increase soil organic matter content. They can also enhance productivity of the primary crops by suppressing weed growth and other pests (Strock et al., 2004).

With regard to cover crops, the type a farmer selects will generally depend on the problem(s) being addressed, such as preventing erosion, supplying N through fixation, suppressing pests, or simply rotating crops for a higher yield (Snapp et al., 2005). Cereal grains are among the types of cover crops that have been incorporated into various rotations (Vyn et al., 2000). In comparison to legume cover crops, cereal cover crops have the greatest amount of biomass and should be considered when the goal is to build soil organic matter (Snapp et al., 2005). Using a winter cover crop following corn (especially when it has been harvested for silage) has been shown to be beneficial for nutrient management in the Midwest (Ruffo et al., 2004). Environmental and economic benefits of cover crops partially depend on an accurate estimate of the N fertilizer requirement of subsequent crops and whether profitability can be enhanced through reductions in fertilizer N requirements (Vyn et al., 2000).

Balancing fertilizer N inputs is important for both productivity and environmental quality. An optimum amount of plant-available N is needed to maintain grain yield and protein, but excess N fertilizer can increase residual soil nitrate after harvest (Lloveras et al., 2001). Grain yield, protein, and quality will also vary among years because of differences in the amount of precipitation, temperature patterns, landscape position, and other factors (Fiez et al., 1994; Fowler, 2003; Lopez-Bellido et al., 2006). As a result, residual soil nitrate may have very little to do with fertilizer N rates (Lloveras et al., 2001). Tillage can influence N availability and grain protein. For example, Al-Kaisi and Licht (2004) reported greater N use efficiency with no-till than conventional cropping systems.

Triticale introduction into a cropping system will allow uptake of residual N from the previous crop in the rotation. Winter rye cover crops have proven to be excellent at scavenging residual soil NO_3-N from the root zone (Kessavalou and Walters, 1997, 1999). Rye captured an average 34 kg N Mg^{-1} aboveground dry matter yield as a cover crop following soybean (Kessavalou and Walters, 1997). Because triticale parentage comes from both rye and wheat (*Triticum aestivum* L.), it may have some of the same beneficial characteristics as rye.

Triticale, Nitrogen and Soil Quality Interactions

Nitrogen is essential for plant growth (Di and Cameron, 2002) but can be lost to both surface water and groundwater resources if it is not properly managed. Nitrogen management is closely associated with soil quality because of its cycling through the organic matter fraction. Therefore, an awareness of the complexity and cycling of soil organic matter within cropping systems is needed to minimize the environmental risk associated with N use and to improve the economic return to farmers (Bundy and Andraski, 2005).

A well-developed N management plan is essential to ensure economic and environmental compatibility within a cropping system (Jaynes et al., 2001). As an input to soil, N comes from both the atmosphere (primarily through fixation but also with rainfall) and external sources, such as fertilizer or animal manure. Nitrogen management, including timing and rates of fertilizer application as well as having living plants present to take up N as it is being cycled within the soil, is important for preventing N losses from the soil to surface or ground water resources (Kanwar et al., 1996). When multiple sources of N are involved, management plans must consider the particular soil, hydrology, crop sequence, and the tillage practice being used within a field (Meisinger and Delgado, 2002). The amount of supplemental N needed to optimize crop productivity will be dependent upon how much plant available N is in the soil. Dinnes et al. (2002) stated that for many Midwestern U.S. soils, N management strategies to reduce NO_3-N losses must account for potential N loss through tile drainage systems. These concepts are important for all cropping systems, including the introduction of triticale, because of the strong relationships between N fertilizer rate, crop yield, soil water movement, and nitrate leaching.

It is also important to understand N cycling and its relationship to soil quality at both the farm-to-farm and region-to-region basis because an imbalance in N cycling is a primary cause for excess pools of residual N in the soil. These pools of N (generally in the form of nitrate) are the cause for major losses of N from the soil to surface water, groundwater, and the atmosphere (Follett and Delgado, 2002). Excessive loss of nitrate from extensive use of N fertilizers for crop production is why the central U.S. has been blamed as a major contributor to hypoxia in the Gulf of Mexico (Balkcom et al., 2003). This accusation is supported by a study (Balkcom et al., 2003) that showed Iowa rivers have high concentrations of nitrate that have been traced back to the management practices associated with row crop production. In Illinois, the average rate of N fertilization on all cropland is 87 kg N ha^{-1} (David and Gentry, 2000), but the areas planted to corn receive an average rate of 100 to 200 kg N ha^{-1} (David et al., 1997). Nitrate leaching into subsurface drainage waters has thus become a major issue in Iowa due to the increased use of N fertilizer and changes in cropping systems during the past 50 years.

Randall and Mulla (2001) discussed how row crops lose more nitrate than perennial crops and how losses are affected less by tillage than N management. Fertilizer management has a major role, but N loss also depends on soil and climatic conditions (Di and Cameron, 2002). For example, Donner (2004) showed that nitrate leaching was lower in soybean than corn, but losses with winter wheat were even lower because the vegetative cover provided by the wheat crop reduced the amount of water percolation that would normally result in nitrate leaching (Zhu and Fox, 2003). Jaynes et al. (2001) showed that most of the fall nitrate lost from an Iowa soil is more related to late season rainfall and subsequent leaching than fertilizer used or the crop that was grown. They also found most nitrates in the top 30 cm of the soil could be recovered by subsequent crops, but nitrate at depths of 90 cm or more was more likely to be leached from the soil profile.

The specific effects of triticale incorporation into a cropping system on soil quality have yet to be determined. Before doing so it is important to understand soil quality as a concept. Defined as "the capacity of the soil to function," the soil quality concept is beginning to be recognized as important by farmers, ranchers, environmentalists, politicians, and researchers. Soil quality assessment is being used not only across the USA, but around the world, as a way to evaluate how soil and crop management practices affect a soil's ability to produce food, feed and fiber and how those practices affect the environment (Karlen et al., 1997, 2002). To fully comprehend the soil quality concept, it is very important to recognize that soil quality or soil health are general terms and that many different factors can influence soil resources in a positive or negative manner (Smith and Doran, 1996).

Assessment of soil quality requires the user to be aware of the multiple functions soil provides and their variation in time and space (Larson and Pierce, 1991). This variation reflects the multitude of biogeochemical processes that affect soil physical, chemical, and biological properties and processes. It is also one reason several different indicators and assessments are needed to fully characterize soil quality.

Tillage, crop rotation, and nutrient management are among the practices that have a major effect on soil quality (Anderson et al., 1997). Improper, shortsighted, or poor management decisions can result in soil degradation through erosion, compaction, clearing or nutrient imbalances (Ridgway, 2002). Some suggest soil degradation has become worse over the past 50 years and that if policy makers fail to act, this degradation will severely impact agricultural food supplies (Scherr, 1999). Uncontrolled soil degradation could result in lower farmland values and yields, thus increasing prices as the demand for products increase (Scherr, 1999). Soil degradation also plays important roles with regard to soil water and nutrient balance within the root zone and the transport of agricultural chemicals into surface and groundwater resource (Kocyigit, 2004).

Assessing Soil Quality

Complete assessments are needed because soil quality can be degraded in several ways other than soil erosion or soil N status. Degradation can result from declines in organic matter, compaction, salinization, acidification, alkalinization, nutrient depletion, and chemical or heavy metal contamination. Reduced biological diversity and activity of soil organisms can also reflect reduced soil quality (Brejda et al., 2000). Soil functions that determine soil quality include the ability to accept, hold, and release nutrients and other chemical constituents; to accept, hold, and release water to plants and surface and groundwater recharge; to promote and sustain root growth; to maintain suitable soil biotic habitat; to respond to management; and to resist degradation (Larson and Pierce, 1991).

The effects of land use and conservation practices on soil functions must be inferred by monitoring changes in the soil attributes or indicators that characterize it (Brejda et al., 2000). Some important soil functions include: water flow and retention, solute transport and retention, physical stability and support; retention and cycling of nutrients; buffering and filtering of potentially toxic materials and maintenance of biodiversity and habitat (Daily et al., 1997). The appropriate indicators for assessing soil quality are dependent upon scale and function. For example, Bredja et al. (2000) used the National Resource Inventory to show that total organic C and total N would be good indicators of soil quality at a regional scale. The important point is that regardless of scale, the soil quality indicators used for an assessment should correlate well with ecosystem processes, integrate soil properties and processes, be accessible to many users, sensitive to management and climate, and whenever possible be components of existing databases (Andrews et al., 2004).

In terms of soil quality, soil C affects water retention, aggregate formation, bulk density, pH, buffer capacity, cation-exchange properties, mineralization, sorption of pesticides and other agrichemicals, color, infiltration, aeration, and the activity of soil organisms (Larson and Pierce, 1991). Currently, there is no information on how triticale will affect soil C and other soil quality indicators.

To assess soil quality the user begins by establishing broad goals such as sustaining plant and animal productivity, maintaining or enhancing water air quality, or supporting human health and habitation (Karlen et al., 1997). To facilitate these assessments, a framework (Andrews et al., 2004) has been developed to quantify the impact of soil and crop management practices on soil function. The framework consists of three steps: indicator selection, indicator interpretation, and integration into an index. The framework is designed for adaptive soil resource management or monitoring and is transferable to a variety of climates, soil types, and soil management systems.

A database that includes management goals, critical soil functions to attain those goals, and other site-specific factors such as crop sensitivity and region are included in the framework (Andrews et al., 2004). For detailed information about the soil quality assessment framework, also referred to as the Soil Management Assessment Framework or SMAF, the reader is referred to Andrews et al. (2004). In general, however, after selecting the indicators and measuring them, interpretation involves transforming each of the value to a unit less value using nonlinear scoring curves so that the scores for the various parameters can be combined into a single value. It is the use of scoring curves for data analysis and synthesis that allows interpretations to reflect ecosystem functions, farmer and societal values regarding crop production and environmental protection goals (Schiller et al., 2001).

The framework can help select appropriate soil quality indicators, interpret their measurement outcomes, and integrate the interpretations to accurately assess the combined effects of management practices on overall soil function (Andrews et al., 2004). This brief review is intended to show the impact of land use and soil management on agricultural sustainability and environmental quality. Soil quality assessment and N cycling are both complex issues. The important point is that N management, soil quality, and the effect of cropping system can only be evaluated through a systems approach that involves soil and plant analyses and the interpretation of data from well planned and properly conducted soil management experiments (Doran and Jones, 1994).

Conclusions

Incorporating triticale into cropping systems may help reduce soil erosion, capture N from previous crops, improve nutrient cycling, provide a hedge against weather extremes, and prevent leaching of nitrate from the soil. Triticale has many potential uses as cover, forage, grain, and straw. By introducing triticale into Midwestern cropping systems the time between planting of corn and soybean will be lengthened resulting in a rotation effect that may result in greater yields and reduced pesticide use. It will also diversify the predominant corn and soybean system, thus buffering against weather, disease, insect, or market problems.

Quality soil is the basis for productive plant growth in a cropping system and farmers, researchers, and environmentalists are recognizing soil quality assessment as an important tool. There are many indicators of soil quality and many factors must be considered when assessing a soil's ability to support optimum crop growth and yield. Nitrogen is essential for plant growth (Di and Cameron, 2002) and proper N management is required for reducing negative environmental effects associated with N fertilizer additions to cropping systems. Nitrate loss from fertilizer N in the U.S. Corn and Soybean belt has received partial blame for hypoxia in the Gulf of Mexico (Balkcom et al., 2003). Triticale has not been highly researched so there are still many unknowns about how triticale will affect Iowa cropping systems. There is a risk that farmers will initially take when adding winter triticale into a crop rotation, but through controlled research many unknown questions can be answered. The long-term goal of this work is to develop winter triticale into a high-value crop for the farmer while simultaneously lessening many of the current soil and water quality problems facing our nation.

Chapter 3: Soil Nitrate Capture, Forage Production, and Grain Yield of Winter Triticale

A paper to submit to *Agronomy Journal*
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Abstract

Winter triticale (X*Triticosecale* Wittmack) has the potential to reduce nitrate nitrogen (NO_3-N) loss from Iowa cropping systems if grown as a cover crop, for grazing or forage production, or as a grain crop. This research was conducted to quantify N uptake of triticale and to determine the amount of N fertilizer needed to achieve maximum triticale forage and grain yield following either corn (*Zea mays* L.) or soybean (*Glycine max* (L.) Merr.). Triticale was planted near Ames and Lewis, Iowa in 2003 and 2004. Four N fertilization rates (0, 33, 66, 99 kg N ha^{-1}) were evaluated in a randomized complete block design. Triticale grain yield near Ames showed a significant response to the first increment of N (33 kg ha^{-1}), but no additional response to 66 or 99 kg N ha^{-1}. For triticale following corn at Ames, N concentration and total dry matter N increased with higher N rates. Dry matter accumulation increased with the first 33 kg N ha^{-1}, but there was little further dry matter produced from N rates greater than 33 kg ha^{-1}. Overall, for both locations, and prior crops, dry matter accumulation increased steadily between spring regrowth and maturity while N concentration declined. Nitrogen uptake, however, was relatively flat for each location and previous crop. Ames triticale following soybean captured nitrate at N rate 0 kg N ha^{-1} but there was a substantial amount of nitrate that was lost at 33, 66, and 99 kg N ha^{-1}, but triticale following Ames and Lewis corn and Lewis soybean was able to capture a significant amount of soil

nitrate. This research suggests that 33 kg N ha^{-1} is sufficient for triticale growth in Iowa following corn or soybean to have effective triticale N response and grain yield.

Introduction

Nitrogen inputs are necessary for maintaining the productivity of intensive agricultural systems (Follet and Delgado, 2002). However, these inputs can be a major source of non-point source pollution. Several factors including changes in cropping systems, increased artificial drainage, and high rates of N fertilization throughout the U.S. Corn and Soybean Belt have contributed to increased NO_3–N leaching and subsequently have been identified as contributors to higher NO_3–N concentration in surface waters of the region (Balkolm et al., 2003; Jaynes et al., 2001) and hypoxia in the Gulf of Mexico (Donner et al. 2004; Rabalais et al., 2002).

If the concept of sustainable agricultural production systems includes both water quality and productivity, dramatic changes in management practices are required to make current agricultural systems in the U.S. Corn and Soybean Belt sustainable (Jaynes et al. 2001). Addition of crops that capture excess NO_3–N, thus limiting its movement out of crop fields is one option. Winter triticale may fit this need. Other winter cereal grains, most notably rye and wheat, have proven successful as NO_3–N scavenging cover crops (Kessavalou and Walters 1997, 1999; Ruan and Johnson, 1995; Strock et al., 2004). However, the limited growth of cover crops grown between successive summer annual crops may restrict their usefulness for capturing NO_3–N.

Winter triticale may be more useful than short-term cover crops if it is placed in the rotation as a forage or grain crop. It can be planted after a soybean (Schwarte et al., 2005) or corn silage crop in the central Corn Belt and provide valuable forage (Schwarte et al., 2005) or grain for feeding swine (Hale et al., 1985; Myer et al., 1990) or cattle (Hill and Utley 1989; Smith et al., 1994), and straw for either bedding or possibly bioenergy production. Placing winter triticale in the rotation has the potential to capture significant amounts of soil nitrogen (Schwarte et al., 2005), reduce flows from drainage tile (Jaynes et al., 2001; Strock et al., 2004) and buffer against excess residual soil N (Ruan and Johnson, 1995). Triticale introduction into a cropping system may allow uptake of residual N from the previous crop in the rotation.

Proper cultural techniques, including N management, are important for obtaining optimum crop yields and positive economic returns while limiting negative environmental impacts of crop production. Schwarte et al. (2005) reported that planting date plays a key role in the productivity and nitrogen capture of winter triticale in Iowa. Planting in mid- to late-September maximized triticale grain and forage yields when compared to October planting. Total N removal in aboveground dry matter ranged from 52 to 161 kg ha^{-1} depending upon season, location, and planting date. In one of two seasons, N accumulation was 37% greater for mid-September planted triticale than mid-October planting. There was no difference in N accumulation among planting dates during the other season. In both years more than 50% of triticale N uptake occurred by mid-May and nearly 75% of N uptake had occurred by late May. Triticale thus appeared to be efficient in capturing N during the early spring when it is most likely to leach because of high rainfall.

Winter triticale can provide feed, forage, grain, and straw products; reduce environmental problems associated with current cropping practices; and offer other tangible benefits. It grows in the autumn and spring, which provides positive environmental benefits lacking in most cropping systems currently used in the U.S. Corn and Soybean Belt. Before winter triticale will be more widely adopted as a crop option in the Midwestern U.S., nitrogen management for optimum triticale productivity and sustainability must be determined. The objectives of this study were to determine the quantity of N fertilizer needed to optimize winter triticale productivity at two Iowa locations following soybean or corn silage as the previous crop, and determine and identify soil NO_3–N status before and after growing winter triticale. Providing this knowledge will enable farmers and policy makers to make better decisions regarding cropping system improvements that reduce NO_3–N loss from crop fields and improve management decisions regarding triticale production and utilization.

Materials and Methods

The response of winter triticale (X*Triticosecale Wittmack*) to four nitrogen (N) fertilizer rates applied following corn or soybean was evaluated during 2003-2004 and 2004-2005 at two Iowa locations. Trials were conducted in central Iowa at the Iowa State University (ISU) Bruner Farm near Ames (42.0°N, 93.6°W, 291 m) and in southwest Iowa at the ISU Armstrong Research and Demonstration Farm near Lewis (41.2°N, 95.1°W, 370 m). The predominate soil types were Clarion loam (Fine-loamy, mixed, mesic Typic Hapludolls) at the Bruner Farm in both years, Marshall silty clay loam (Fine-silty, mixed, mesic Typic Hapludolls) at Lewis in 2003-04, and Exira silty clay loam (Fine-silty, mixed, mesic Typic Hapludolls) at Lewis in 2004-05.

Crop Culture and Nitrogen Application

Corn and soybean crops were grown before winter triticale at both sites. Fields in Ames were prepared for corn and soybean planting with one pass of a field cultivator. No preplant tillage was used at Lewis. The corn and soybean were planted in alternating strips, 9.15 m wide (12 rows with 0.762 m between rows) and 21.3 m long. An early maturity group

(II) soybean was grown at both sites to ensure an optimum triticale planting date (Schwarte et al., 2005). Corn was harvested as silage and soybean was harvested as grain with the residue returned to the field. Dates of important field activities and sampling activities are contained in Table 1.

Soil tests at Ames indicated 40 mg kg^{-1} P, 250 mg kg^{-1} K, and pH 6.5 in Oct 2001 and 27 mg kg^{-1} P, 160 mg kg^{-1} K and pH 6.9 in Oct 2004. Soil tests at Lewis indicated 23 mg kg^{-1} P, 207 mg kg^{-1} K and pH 6.5 in Oct 2003 and 25 mg kg^{-1} P, 167 mg kg^{-1} K, and pH 7.3 in Oct 2004.

At Ames in 2003, corn ('Dekalb DKC64-11 RR', 114 d relative maturity) was planted at 79,535 seeds ha^{-1} and soybean ('Dekalb DKB17-51 RR', 1.7 relative maturity) was planted at 395,200 seeds ha^{-1} on 20 May. For Ames in 2004, the same corn hybrid and soybean cultivar were planted at the same densities on 5 May. Nitrogen fertilizer was applied to corn at 134 kg ha^{-1} in the form of urea on 9 June 2003 and in the form of injected (320 g kg^{-1}) UAN solution on 16 June 2004. The corn was cultivated between the rows on 9 June 2003. Roundup Ultramax was applied to the soybean and corn at 1.9 L ha^{-1} on 16 June 2003. Roundup Weathermax was applied to the soybean and corn at 1.8 L ha^{-1} on 15 June 2004.

At Lewis in 2003, corn ('Channel 7699C', 109 d relative maturity) was planted at 79,040 seeds ha^{-1} on 27 Apr and soybean ('Pioneer 92B05 RR', 1.9 relative maturity) was planted at 395,200 seeds ha^{-1} on 13 May. In 2004, corn ('Nutrident C 1153 ND', 115 d relative maturity) was planted on 19 Apr and soybean ('Pioneer 92B05 RR', 1.9 relative maturity) was planted on 23 Apr. The same planting densities were used in 2004 and 2003. Weed management in 2003 consisted of 55 mL ha^{-1} Steadfast, 7.7 L ha^{-1} Callisto, 1.1 kg ha^{-1} Atrazine applied to corn on 7 June and 1.6 L ha^{-1} Roundup Weathermax applied to soybean on 20 June. Weed management in 2004 consisted of interrow cultivation of corn on 15 June and 1.5 L ha^{-1} Roundup Weathermax applied to soybean on 15 June.

Winter triticale ('DANKO Presto' in 2003, 'NE426GT' in 2004) was seeded at 320 seeds m^{-2} with a Tye® model 2007 no-till drill (AGCO Corp., Lockney, TX). The row spacing was 20.3 cm. No tillage was performed between corn or soybean harvest and triticale planting at either site.

Four N fertilizer rates (0, 33, 66, or 99 kg N ha^{-1}) were assigned to each pair of triticale plots growing on the harvested corn and soybean strips. The N fertilizer was applied at Ames using a Gandy model 1010T-TBM (Gandy Co., Owatonna, MN) spreader with a 3 m width and at Lewis with a Gandy model 6500 spreader with a 1.5 m width. Ammonium nitrate (NH_4NO_3) was used as the N fertilizer source at both locations.

Plant Measurements

Corn silage was harvested with forage chopper and weighed. Silage yield was calculated for the entire site and adjusted to 650 g kg^{-1} moisture content. Soybean was combine harvested and weighed with on-board scales. Soybean grain yield was calculated for the entire site and adjusted to 130 g kg^{-1} moisture content. Triticale dry matter production was determined once in late fall just after the crop became dormant and every three weeks (four times) in the spring starting with the first week of May (Table 1). A 48.3-cm length of row was harvested from two randomly selected areas within each plot. The two samples for each plot were combined, oven dried at 65°C for at least 48 h, and weighed. A sub sample was taken after weighing and ground to pass a 2 mm screen using a Thomas-Wiley mill (Model 4, Thomas Scientific, Swedesboro, NJ). The sample was ground a second time using an Udy Cyclone Sample Mill (Udy Corporation, Inc., Ft. Collins, Co) to pass a 0.5 mm screen. These ground samples were analyzed by dry combustion in a Fison NA 1500 Elemental Analyzer (Fison Instruments SpA, Milan, Italy) to determine total N concentration of the harvested dry matter (AOAC, 2000).

Triticale grain was harvested with a Massey 25 combine at Ames and a JD 4420 combine at Lewis, both equipped with electronic weighing systems. The harvested area in each plot was 3.66 m wide by 21.34 m long at Ames and 4.57 m wide by 21.34 m long at Lewis. Grain sub samples (approximately 2000 g) were collected to determine moisture content, 1000 kernel weight, and test weight. Crop residue and other debris were removed from the grain samples with a seed cleaner (Office Model Clipper, Ferrel Ross, Bluffton, IN). A thousand seeds were counted with an electronic seed counter (Model 850-2, The Old Mill Co., Savage, MD) and weighed. Moisture content and test weight were determined on the cleaned grain using a grain analysis computer (Model GAC2100, Dickey-John, Auburn, IL). Final grain yields were adjusted to 135 g kg^{-1} moisture content. The triticale grain was ground using a Magic Mill III Plus Grain Mill (K-Tec, Orem, UT) and analyzed for moisture using AACC Method 44-15A (AACC, 2003) and total N concentration by dry combustion (AOAC, 2000) in a Fison NA 1500 Elemental Analyzer (Fison Instruments SpA, Milan, Italy).

Spikes m^{-2} and kernels $spike^{-1}$ was measured using whole-plant samples collected the day of combine harvest. The number of spikes m^{-2} was determined by sampling 48.3 cm of row from two areas of each plot (0.2 m^2) and counting the total number of spikes. Kernels $spike^{-1}$ was determined by harvesting ten consecutive spikes from two areas within each plot and counting the kernels threshed from the 20 spikes. Straw samples were collected from the swath created by the combine.

Soil NO_3-N Measurements

Soil profile NO_3-N concentrations were determined on soil cores collected before triticale planting and after triticale grain harvest at each production site (Table 1). Cores were collected to a depth of 1.2 m using a truck-mounted Giddings hydraulic sampling probe (#10-SC Model Giddings Machine Company Inc. Windsor, CO) with a 3.8 cm diameter. Two soil cores were taken from each plot and divided into 0- to 15-cm, 15- to 30-cm, 30- to 60-cm, 60- to 90-cm, and 90- to 120-cm depth increments. Soil moisture was determined by drying a 15 g sub sample at 105°C for 18 h in a forced-air oven. Bulk density for each soil depth increment was computed by multiplying the wet soil mass for the known sampling volume by 1 minus the moisture content (in decimal fraction) and dividing by the volume. Samples from similar depths in each plot were combined, mixed, pushed to pass an 8-mm screen, air dried, and crushed. A 20 g dry weight sub sample of the soil for each depth increment in a plot was extracted with 100 ml of 2 M KCl and analyzed colorimetrically for NO_3-N (Keeney and Nelson, 1982) using flow injection analysis (Latchat Instruments, Milwaukee, WI). Nitrate-N concentration was multiplied by bulk density to determine the quantity of NO_3-N throughout the soil profile.

Weather Data

The daily minimum temperature, maximum temperature, and rainfall were recorded for 2003, 2004, and 2005 using weather stations at each location. The mean weather conditions for each site were determined using means from 1951 to 2005 from the Iowa Environmental Mesonet (2005). Daily rainfall measurements did not include frozen precipitation, which was not measured. Growing degree days (GDD, 0°C base temperature) were calculated using the equation:

$$GDD = \Sigma \{[(\text{daily maximum temp.} + \text{daily minimum temp.})/2] - \text{base temp.}\} > 0$$

Statistical Design and Analysis

The statistical design for these field experiments was a randomized complete block with separate analyses for each location and previous crop combination. The corn and soybean strips that preceded the triticale crops were not randomized because of the difficulty it would have created for managing those crops. However, this lack of randomization meant the statistical analysis for winter triticale response to N fertilizer rates required separate analysis for each prior crop. The variance for each factor measured was stabilized through transformation according to the procedure of Box and Cox (1978). Analysis of variance (ANOVA) was performed on the transformed data using the GLM procedure of SAS (SAS Inst., Inc., Cary, NC). A combined analysis was performed over years. Main effects of nitrogen rate and the nitrogen rate by year interaction were analyzed using an F test. The F test for nitrogen rate was calculated using the mean squares for the year by nitrogen rate interaction. The F test for the nitrogen rate by year interaction was calculated using the error mean square. Too few years were included in the experiment to test it as a main effect (Gomez and Gomez, 1994). Tukey's test was used to make mean comparisons at the $P \leq 0.05$ level (Steel and Torrie, 1980).

Temporal changes in dry matter accumulation, N concentrations, and N accumulation in the spring and summer were analyzed with regression and ANOVA techniques. The data for four sampling dates in each year were converted from calendar time to thermal time (GDD). Regression analysis was used to fit a line to the four measured data points for each plot. A second-order polynomial line was fit to dry matter and N accumulation responses to thermal time. A type III exponential function (Sit and Poulin-Costello, 1994) was used to fit

N concentration response to thermal time. Predicted values were calculated for each 200 GDD interval by solving the regression equations. The predicted values at each 200 GDD increment were compared for statistical significance at $P \leq 0.05$ level using ANOVA. Regression equations were developed for the main effects of each N rate and plotted for visualization of the responses.

Results and Discussion

Previous Crop Yields

Climatic conditions supported high corn silage yields in 2003 and 2004 and high soybean yields in 2004 (Figures 1 and 2). Low rainfall in August 2003 stressed soybean at both sites, decreasing grain yield. Corn silage yield at the Ames site was 46.8 Mg ha^{-1} in 2003 and 53.5 Mg ha^{-1} in 2004, both greater than the five-year county average (NASS, 2006) of 43.7 Mg ha^{-1}. Silage yields near Lewis, were 34.7 Mg ha^{-1} in 2003 and 55.3 Mg ha^{-1} in 2004, compared to a 5-year average county yield of 37.2 Mg ha^{-1}. Grain yield of soybean near Ames was 2.2 Mg ha^{-1} in 2003 and 3.4 Mg ha^{-1} in 2004 compared to a 5-year average of 2.9 Mg ha^{-1}. At Lewis, soybean yield was 2.0 Mg ha^{-1} in 2003 and 3.0 Mg ha^{-1} in 2004 compared to a 5-year average of 2.9 Mg ha^{-1}.

Dry Matter and Nitrogen Accumulation

The November through April period was warmer than average in both 2003-2004 and 2004-2005 resulting in little to no winter injury of triticale at either site (Figures 1 and 2). This resulted in rapid spring regrowth in both years. For triticale following corn or soybean at Ames and Lewis, dry matter accumulation, N concentration, and N uptake were calculated for each 200 GDD period following spring regrowth. The responses of these three parameters to N rate were tested using ANOVA (Table 2).

For triticale following corn at Ames, N rate was significant for all three parameters. Following soybean at Ames, N rate differences were significant for plant N concentration and plant N removal at each 200 GDD increment. However, dry matter accumulation response to N rate was significant only at 1600 to 1800 GDD. There was a response to increasing N rates in triticale following corn at Lewis for plant N concentration at each 200 GDD increment and plant N removal for GDD 800 to 1400. However, dry matter accumulation did not respond to increasing N rates. For triticale following soybean at Lewis there was no response to increasing N rate for dry matter accumulation or plant N removal, N rate was significant for plant N concentration at 800 GDD.

The responses for all three parameters to N rate, location, previous crop and GDD are shown graphically in Figures 3 and 4. The lowest dry matter, N concentration, and N uptake values were always associated with the control (0 kg N ha^{-1}) after each of the previous crops at both Ames and Lewis. Following corn at Ames, triticale dry matter accumulation, N concentration, and N uptake generally increased with higher N rates and were highest with 99 kg N ha^{-1}. For triticale following soybean at Ames, N concentration and total dry matter N increased with higher N rates. Dry matter accumulation increased with the first 33 kg N ha^{-1}, but there was little further dry matter produced from N rates greater than 33 kg ha^{-1}. Following both corn and soybean at Lewis, triticale dry matter accumulation and dry matter N were greater for 66 and 99 than 0 and 33 kg N ha^{-1}.

Overall, for both locations, and prior crops, dry matter accumulation increased steadily between spring regrowth and maturity while N concentration declined. Nitrogen uptake, however, was relatively flat for each location and previous crop. This suggests the triticale grown in these studies had accumulated the maximum amount of N it was going to take up from the soil before the early May sampling. This differs from studies by Schwarte et al. (2005) who found triticale accumulating N through the middle to latter part of May. Variety differences, seasonal weather patterns, and the rate of GDD accumulation are all factors that may have contributed to this difference in N uptake. With regard to enhancing sustainability of Midwest cropping systems, there is little difference in whether N uptake is maximized before or after May 1st. Either way, incorporating triticale into the crop rotation could have positive environmental effects because N that may be accumulating in the soil profile and potentially leaching with the drainage waters would be removed by growing an over-wintering crop such as triticale.

Triticale Grain Yields and Quality

The lowest triticale grain yield after corn in Ames was produced when no N fertilizer was applied (Table 3). Applying 33 kg N ha^{-1} increased grain yield by 64% when compared to 0 N. Nitrogen applications of 66 and 99 kg ha^{-1} produced grain yields similar to 33 kg ha^{-1}. Of the three yield determining components, spikes m^{-2} and seeds spike^{-1} were increased by application of N fertilizer to triticale grown after corn at Ames. Kernel weight was unchanged across N rates. Applying 33 kg N ha^{-1} to triticale grown after soybean in Ames increased grain yield by 24% when compared to 0 N. However, there was no difference in grain yield for 0, 66, and 99 kg ha^{-1} or 33, 66, and 99 kg ha^{-1}. Seeds spike^{-1} was the only yield component that was significantly increased with addition of N. Triticale grain yield and yield components did not respond to N application after corn or soybean at Lewis. The 2004 triticale crop was affected by *Septoria* leaf blotch (*Septoria* spp.) due to the cool, moist conditions during June and July at both sites (Figures 1 and 2). This disease was presumably a major factor responsible for low grain yield in 2004 regardless of the previous crop.

Grain moisture, test weight, and ergot percent were not affected by N applied to triticale grown after corn or soybean at Ames. Lodging in triticale at Ames was unaffected by N rate after corn, but was increased with higher N rates following soybean. Moisture in triticale grain produced after corn at Lewis was greatest when 0 N was applied and decreased with increasing N rates. Grain moisture after soybean at Lewis was not influenced by N application rate. There were no N differences in the test weight for the various N rates applied to triticale after soybean at Lewis. However, addition of higher amounts on N decreased the test weight of grain produced after soybean at Lewis. The amount of ergot in the grain was similar among the N rate treatments after both corn and soybean at Lewis. Lodging in triticale after corn or soybean at Lewis was unaffected by N rate.

Fall Dry Matter, Fall N Concentration, Straw N, and Grain N

There was no significant response to N application for fall dry matter, fall N concentration, fall N accumulation, grain N concentration or grain N accumulation of triticale following corn or soybean at Ames or Lewis (Table 4). Straw N concentration increased with N rate when triticale followed soybean at Ames and corn or soybean at Lewis.

Soil Nitrate and N Balance

Soil nitrate was measured from various soil depths up to 120 cm below the soil surface (Table 5). Partial mass balance of N for each nitrogen treatment (Karlen et al., 1998) was determined by assuming the conservation of mass:

Σ inputs - Σ outputs = N balance

Pre plant soil NO_3-N (residual from previous crop) and nitrogen fertilizer were the two inputs used in the budget and plant removal and post-harvest soil NO_3-N were the two outputs.

There was a substantial amount of residual soil nitrate available to the triticale crop regardless of the previous crop (Tables 5 and 6). Average preplant soil NO_3-N to a depth of 120 cm was 48 kg ha^{-1} after corn silage at Ames, 70 kg ha^{-1} after soybean at Ames, 76 kg ha^{-1} after corn silage at Lewis, and 80 kg ha^{-1} after soybean at Lewis. More than half of the residual soil NO_3-N after corn silage or soybean was found in the top 15 cm of the soil profile and about three-fourths was found in the top 30 cm. This could be due to greater organic matter in the topsoil layer.

For the most part, soil NO_3-N levels were not affected by fertilizer N applications in the range of 0 to 99 kg ha^{-1} in our study (Tables 5 and 6). There were two exceptions. Post-triticale soil NO_3-N at 0 to 15 cm after corn silage at Lewis was 7.9 kg ha^{-1} for 66 kg N ha^{-1} compared to 4.8 kg ha^{-1} for the other three N fertilizer rates. Similarly, at 90 to 120 cm the post-triticale NO_3-N after corn silage at Lewis for 66 kg N ha^{-1} was 2.7 kg ha^{-1} compared to an average of 0.7 kg ha^{-1} for the other three N fertilizer rates. Nitrate change also had an N response following corn silage at Lewis at a depth of 0-15 since the mean for N rate 66 kg N ha^{-1} was higher than any of the other N rates. Soil NO_3-N was lower after growing triticale at all depths when the previous crop was corn silage or soybean. Reductions in NO_3-N to a soil depth of 120 cm from growing triticale were 33 kg ha^{-1} after corn silage at Ames, 53 kg ha^{-1} after soybean at Ames, 45 kg ha^{-1} after corn silage at Lewis, and 52 kg ha^{-1} after soybean at Lewis.

Jaynes et al. (2001) showed that the fall nitrate lost from an Iowa soil is more related to late season rainfall and subsequent leaching than fertilizer used or the crop that was grown. They also found most nitrates in the top 30 cm of the soil could be recovered by subsequent crops, but nitrate at depths of 90 cm or more was more likely to be leached from the soil profile. In this study, growing winter triticale depleted most of the soil nitrate below 60 cm.

N removal by the triticale crop at Ames increased with N application rates up to 66 kg ha^{-1}. Similar trends occurred for triticale grown after corn and soybean at Lewis, but *P* values for the F-test of N rate were >0.05 due to high plot-to-plot variability. There was also a trend toward greater estimated N loss with increasing N rates after both corn silage and soybean at the two sites, but differences among N rates were only significant at the $P \leq 0.05$ level for triticale grown after soybean at Ames. In many cases, estimated N loss were negative indicating a net gain in N during the growing season. The greatest estimated N loss was 37 kg ha^{-1} for triticale grown with 99 kg ha^{-1} after soybean at Ames. Estimated N loss was negative at all N fertilizer rates when triticale was grown after corn silage or soybean at Lewis. N losses from growing triticale using N rates that maximized dry matter and grain production were much less than the 21 to 180 kg ha^{-1} annual losses of NO_3-N from the upper 90 cm of the soil with continuous corn in Iowa (Karlen et al., 1998).

In most cases, less N was removed in the triticale grain than in the stems and leaves. When no N fertilizer was applied, 42 to 68% of the N removal by the triticale occurred in the grain. When N fertilizer was applied at rates between 33 and 99 kg ha^{-1}, 31 to 41% of the N removal was in the grain. The differences in N removal that would occur with a triticale crop grown exclusively for grain relative to one grown for forage or grain and straw could have a significant impact on the N status of the soil during the production of subsequent crops. When grown exclusively for grain, N in triticale leaves and stems would be returned to the soil. As these residues decay, some of this N could be available for plant uptake by subsequent crops or lost to leaching or volatilization.

Conclusions

Nitrogen management, including timing and rates of fertilizer application as well as having living plants present to take up N as it is being cycled within the soil, is important for preventing N losses from the soil to surface or ground water resources (Kanwar et al., 1996). Winter triticale grown after either corn silage or soybean as a cover crop, supplemental forage, or grain crop can capture a significant amount of soil NO_3-N. An optimum amount of plant-available N is needed to maintain grain yield and protein, but excess N fertilizer can increase residual soil nitrate after harvest (Lloveras et al., 2001). Only 33 kg N ha^{-1} fertilizer was needed for optimal dry matter production and grain yield of winter triticale in the two Iowa sites used in this study. Reductions in NO_3-N to a soil depth of 120 cm from growing triticale were 33 to 53 kg ha^{-1}. Since a triticale crop accumulates the majority of its N before the middle of May, this crop can improve Iowa cropping systems by reducing N loss from the soil during the winter and early-spring months. This research has provided necessary information with regard to optimum N fertilizer rates for an environmentally safe cropping system that can produce high-quality grain for Iowa farmers.

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Table 1 Timeline for field activities.

Activity	2003-04 Ames	2003-04 Lewis	2004-05 Ames	2004-05 Lewis
Previous crop harvest				
Corn silage	8-Sept.	1-Sept.	15-Sept.	10-Sept.
Soybean grain	15-Sept.	17-Sept.	9-Sept.	9-Sept.
Preplant soil NO_3-N sampling	23-Sept.	25-Sept.	27-Sept.	15-Sept.
Planting	26-Sept.	24-Sept.	28-Sept.	25-Sept.
N fertilization	23-Mar.	23-Mar.	21-Mar.	17-Mar.
Dry matter sampling				
Fall	21-Nov.	24-Nov.	17-Nov.	22-Nov.
Spring 1	4-May	5-May	5-May	2-May
Spring 2	1-June	28-May	26-May	25-May
Spring 3	18-June	16-June	15-June	13-June
Spring 4	7-July	8-July	5-July	5-July
Triticale grain harvest	15-July	14-July	11-July	13-July
Post harvest soil NO_3-N sampling	22-July	26-July	25-July	21-July

Table 2. ANOVA for dry matter accumulation, N concentration, and N removal of winter triticale following corn or soybean at Ames and Lewis, IA in the 2003-2004 and 2004-2005 growing seasons. Data used for the analysis was transformed using the natural logarithm to stabilize the variance.

Source	df	Accumulated growing degree days (°C) †						
		600	800	1000	1200	1400	1600	1800
		P>F						
		Ames, Corn						
Dry matter accumulation								
Nitrogen (N)	3	0.0418	0.0330	0.0253	0.0168	0.0097	0.0048	0.0024
Y × N	3	0.2514	0.1941	0.2428	0.3095	0.4482	0.6993	0.8933
N Concentration								
Nitrogen (N)	3	0.0034	0.0010	0.0022	0.0055	0.0106	0.0167	0.0228
Y × N	3	0.8899	0.9444	0.8805	0.7772	0.6938	0.6386	0.6078
Total Dry Matter N								
Nitrogen (N)	3	0.0036	0.0081	0.0118	0.0127	0.0122	0.0141	0.0231
Y × N	3	0.7185	0.3830	0.2348	0.2163	0.2508	0.2553	0.1913

† Growing degree days (base 0°C) accumulated after 1 March. Daily growing degree days were calculated as Σ {[(daily maximum temp. + daily minimum temp.)/2] – base temp.}>0.

Table 2. (continued)

Source	df	Accumulated growing degree days (°C)						
		600	800	1000	1200	1400	1600	1800
		$P>F$						
				Ames, Soybean				
Dry matter accumulation								
Nitrogen (N)	3	0.0629	0.0597	0.1232	0.1261	0.0896	0.0380	0.0444
Y × N	3	0.6112	0.2404	0.0511	0.0266	0.0382	0.3517	0.7795
N Concentration								
Nitrogen (N)	3	0.0239	0.0122	0.0076	0.0054	0.0043	0.0036	0.0031
Y × N	3	0.1979	0.1836	0.2722	0.4087	0.5303	0.6237	0.6929
Total Dry Matter N								
Nitrogen (N)	3	0.0251	0.0019	0.0021	0.0053	0.0049	0.0005	0.1090
Y × N	3	0.3305	0.7831	0.7756	0.5745	0.5061	0.9417	0.5951

Table 2. (continued)

Source	df	Accumulated growing degree days (°C)						
		600	800	1000	1200	1400	1600	1800
		P>F						
				Lewis, Corn				
Dry matter accumulation								
Nitrogen (N)	3	0.3120	0.1316	0.1027	0.1005	0.1077	0.1175	0.1424
Y × N	3	0.5247	0.7670	0.8124	0.7772	0.6682	0.4841	0.3324
N Concentration								
Nitrogen (N)	3	0.0254	0.0135	0.0112	0.0126	0.0161	0.0200	0.0241
Y × N	3	0.4476	0.3080	0.2315	0.2673	0.3258	0.3776	0.4119
Total Dry Matter N								
Nitrogen (N)	3	0.0864	0.0442	0.0282	0.0282	0.0417	0.0696	0.1173
Y × N	3	0.3344	0.4336	0.6167	0.6401	0.4728	0.1872	0.0826

Table 2. (continued)

Source	df	Accumulated growing degree days (°C)						
		600	800	1000	1200	1400	1600	1800
		$P>F$						
				Lewis, Soybean				
Dry matter accumulation								
Nitrogen (N)	3	0.7991	0.4074	0.3438	0.3642	0.4228	0.4873	0.4961
Y × N	3	0.1212	0.0651	0.1514	0.2143	0.2270	0.1907	0.1261
N Concentration								
Nitrogen (N)	3	0.1090	0.0429	0.0587	0.1111	0.1745	0.2341	0.2874
Y × N	3	0.4581	0.6071	0.5285	0.4048	0.3302	0.2916	0.2686
Total Dry Matter N								
Nitrogen (N)	3	0.2356	0.3953	0.6247	0.7336	0.6868	0.3995	0.0543
Y × N	3	0.1453	0.0315	0.0127	0.0111	0.0140	0.0399	0.3995

Table 3. Triticale yield, yield components, and grain quality as affected by location, previous crop, and N rate.

			N rate (kg ha^{-1})			
Parameter	Transformation	*P(F)*	0	33	66	99
			Ames, Corn			
Grain yield (Mg ha^{-1})	Log	0.016	2.10b†	3.44a	3.51a	3.51a
Spikes m^{-2} (no.)	Square root	0.005	340b	455a	478a	512a
Seeds $spike^{-1}$ (no.)	Square root	0.021	35b	39ab	38ab	42a
Kernel weight (mg)	Reciprocal	0.698	30a	30a	29a	29a
Moisture (g kg^{-1})	Log	0.436	12.8a	12.6a	12.4a	12.5a
Test weight (g hL^{-1})	Reciprocal	0.748	650a	655a	640a	644a
Ergot (mg kg^{-1})	Log	0.500	0.001a	0.024a	0.014a	0.024a
Lodging (%)	Log	0.140	1a	1a	2a	3a
			Ames, Soybean			
Grain yield (Mg ha^{-1})	Log	0.044	3.50b	4.35a	4.07ab	3.86ab
Spikes m^{-2} (no.)	Square root	0.071	457a	566a	584a	559a
Seeds $spike^{-1}$ (no.)	Square root	0.039	35b	38ab	41a	38ab
Kernel weight (mg)	Reciprocal	0.414	30a	30a	28a	27a
Moisture (g kg^{-1})	Log	0.141	12.8a	12.5a	12.3a	12.1a
Test weight (g hL^{-1})	Reciprocal	0.697	655a	659a	643a	645a
Ergot (mg kg^{-1})	Log	0.500	0.045a	0.002a	0.000a	0.010a
Lodging (%)	Log	0.042	1b	8ab	12ab	16a

†Means for treatments within a parameter followed by the same letter are not significantly different according to Tukey's HSD test ($P = 0.05$).

Table 3. (continued)

Parameter	Transformation	$P(F)$	N rate (kg ha^{-1}) 0	33	66	99
			Lewis, Corn			
Grain yield (Mg ha^{-1})	Log	0.120	3.18a†	3.15a	2.80a	2.99a
Spikes m^{-2} (no.)	Square root	0.189	475a	568a	614a	643a
Seeds $spike^{-1}$ (no.)	Square root	0.517	40a	41a	39a	39a
Kernel weight (mg)	Reciprocal	0.487	21a	21a	19a	20a
Moisture (g kg^{-1})	Log	0.040	12.0a	11.8ab	11.7ab	11.6b
Test weight (g hL^{-1})	Reciprocal	0.068	617a	616a	598a	595a
Ergot (mg kg^{-1})	Log	0.741	0.012a	0.008a	0.005a	0.010a
Lodging (%)	Log	0.135	4a	4a	12a	8a
			Lewis, Soybean			
Grain yield (Mg ha^{-1})	Log	0.520	3.99a	3.57a	3.16a	3.70a
Spikes m^{-2} (no.)	Square root	0.573	518a	579a	611a	598a
Seeds $spike^{-1}$ (no.)	Square root	0.141	38a	39a	41a	42a
Kernel weight (mg)	Reciprocal	0.472	23a	21a	20a	20a
Moisture (g kg^{-1})	Log	0.151	12.3a	12.0a	11.6a	11.7a
Test weight (g hL^{-1})	Reciprocal	0.033	634b	631ab	603a	614ab
Ergot (mg kg^{-1})	Log	0.774	0.045a	0.002a	0.000a	0.010a
Lodging (%)	Log	0.291	4a	2a	12a	12a

†Means for treatments within a parameter followed by the same letter are not significantly different according to Tukey's HSD test ($P = 0.05$).

Table 4. Means for triticale fall biomass, plant N, straw N and grain N.

			N rate (kg ha^{-1})			
Parameter	Transformation	*P(F)*	0	33	66	99
		Ames, Corn				
Fall dry matter (Mg ha^{-1})	Reciprocal square root	0.564	0.42a[†]	0.43a	0.43a	0.44a
Plant N – Fall (g kg^{-1})	No transformation	0.338	35.7a	36.5a	34.2a	34.7a
Plant N – Fall (kg ha^{-1})	Log	0.573	15a	16a	15a	15a
Straw N (g kg^{-1})	Square root	0.237	1.8a	3.2a	4.0a	4.4a
Grain N (g kg^{-1})	Reciprocal square root	0.337	15.0a	14.5a	15.6a	17.1a
Grain N (kg ha^{-1})	Log	0.385	30a	27a	32a	38a
		Ames, Soybean				
Fall dry matter (Mg ha^{-1})	Reciprocal square root	0.420	0.60a	0.57a	0.57a	0.64a
Plant N – Fall (g kg^{-1})	No transformation	0.223	38.9a	39.2a	37.5a	36.7a
Plant N – Fall (kg ha^{-1})	Log	0.479	23a	22a	22a	23a
Straw N (g kg^{-1})	Square root	0.032	3.3b	3.7ab	4.1ab	5.0a
Grain N (g kg^{-1})	Reciprocal square root	0.086	14.2a	15.2a	16.6a	18.3a
Grain N (kg ha^{-1})	Log	0.088	26a	30a	35a	43a

[†]Means for treatments within a parameter followed by the same letter are not significantly different according to Tukey's HSD test ($P = 0.05$).

Table 4. (continued)

Parameter	Transformation	$P(F)$	N rate ($kg\ ha^{-1}$) 0	33	66	99
			Lewis, Corn			
Fall dry matter ($Mg\ ha^{-1}$)	Reciprocal square root	0.553	0.64a†	0.60a	0.63a	0.61a
Plant N – Fall ($g\ kg^{-1}$)	No transformation	0.737	34.5a	35.8a	34.4a	35.9a
Plant N – Fall ($kg\ ha^{-1}$)	Log	0.913	22a	22a	22a	23a
Straw N ($g\ kg^{-1}$)	Square root	0.037	5.1b	6.0ab	8.1a	6.8ab
Grain N ($g\ kg^{-1}$)	Reciprocal square root	0.098	18.1a	18.6a	19.3a	20.0a
Grain N ($kg\ ha^{-1}$)	Log	0.119	42a	45a	48a	51a
			Lewis, Soybean			
Fall dry matter ($Mg\ ha^{-1}$)	Reciprocal square root	0.316	0.72a	0.66a	0.66a	0.67a
Plant N – Fall ($g\ kg^{-1}$)	No transformation	0.945	38.7a	39.3a	40.1a	39.6a
Plant N – Fall ($kg\ ha^{-1}$)	Log	0.512	29a	26a	27a	28a
Straw N ($g\ kg^{-1}$)	Square root	0.047	4.8b	5.6ab	6.4a	6.2ab
Grain N ($g\ kg^{-1}$)	Reciprocal square root	0.320	17.4a	19.5a	19.5a	20.3a
Grain N ($kg\ ha^{-1}$)	Log	0.313	39a	49a	53a	49a

†Means for treatments within a parameter followed by the same letter are not significantly different according to Tukey's HSD test ($P = 0.05$).

Table 5. Soil nitrate means for winter triticale grown after corn or soybean at Ames and Lewis, IA in 2004 and 2005.

Depth	Fall Soil NO_3-N		Summer Soil NO_3-N	
	Mean	SE	Mean	SE
		kg ha^{-1}		
		Ames, Corn		
0-15	28.0	1.8	8.3	0.7
15-30	8.9	0.7	3.3	0.4
30-60	5.2	0.4	1.8	0.3
60-90	2.9	0.2	0.7	0.1
90-120	2.5	0.2	0.6	0.2
		Ames, Soybean		
0-15	36.4	1.2	9.6	0.8
15-30	12.8	0.8	3.8	0.2
30-60	9.8	0.7	2.2	0.2
60-90	6.1	0.3	0.9	0.2
90-120	5.1	0.3	0.4	0.1

Table 5. (continued)

Depth	Fall Soil NO_3-N		Summer Soil NO_3-N	
	Mean	SE	Mean	SE
		kg ha^{-1}		
		Lewis, Corn		
0-15	46.5	4.0	18.5	1.3
15-30	9.5	0.7	5.6	0.6
30-60	8.1	0.7	4.6	0.7
60-90	6.6	0.7	1.5	0.2
90-120	5.1	0.5	1.1	0.3
		Lewis, Soybean		
0-15	45.9	3.2	17.5	0.8
15-30	12.6	0.8	4.5	0.5
30-60	8.8	0.7	3.3	0.6
60-90	6.8	0.5	1.2	0.2
90-120	5.4	0.5	1.2	0.3

Table 6. Partial mass budget for N in triticale following corn or soybean at Ames and Lewis, IA in the 2003-2004 and 2004-2005 growing seasons. Soil sampling depth was 0-120 cm for 2003-2004 and 2004-2005 at Ames and 2003-2004 at Lewis. Soil sampling depth was 0-90 cm for Lewis in 2004-2005.

			N rate (kg ha^{-1})			
Parameter	Transformation	*P(F)*	0	33	66	99
		Ames, Corn				
Pre Plant Soil NO_3-N (kg ha^{-1})	Log	0.2492	49a†	46a	47a	48a
Crop Removal (kg ha^{-1})	Log	0.0203	44b	71ab	102a	112a
Post-Harvest Soil NO_3-N (kg ha^{-1})	Log	0.7593	13a	17a	14a	15a
N balance (kg ha^{-1})	Log	0.2864	-7a	-10a	-2a	20a
		Ames, Soybean				
Pre Plant Soil NO_3-N (kg ha^{-1})	Log	0.2647	70a	74a	71a	66a
Crop Removal (kg ha^{-1})	Log	0.0018	60c	86b	105a	108a
Post-Harvest Soil NO_3-N (kg ha^{-1})	Log	0.0834	14a	15a	19a	20a
N balance (kg ha^{-1})	Log	0.0024	-4c	6bc	13b	37a

†Means for treatments within a parameter followed by the same letter are not significantly different according to Tukey's HSD test ($P = 0.05$).

Table 6. (continued)

Parameter	Transformation	$P(F)$	N rate ($kg\ ha^{-1}$) 0	33	66	99
		Lewis, Corn				
Pre Plant Soil NO_3-N ($kg\ ha^{-1}$)	Log	0.3628	76a	71a	70a	78a
Crop Removal ($kg\ ha^{-1}$)	Log	0.1458	89a	114a	153a	164a
Post-Harvest Soil NO_3-N ($kg\ ha^{-1}$)	Log	0.3863	29a	26a	37a	30a
N balance ($kg\ ha^{-1}$)	Log	0.5174	-40a	-37a	-54a	-17a
		Lewis, Soybean				
Pre Plant Soil NO_3-N ($kg\ ha^{-1}$)	Log	0.1729	69a	67a	91a	79a
Crop Removal ($kg\ ha^{-1}$)	Log	0.0574	93a	133a	150a	146a
Post-Harvest Soil NO_3-N ($kg\ ha^{-1}$)	Log	0.0898	21a	21a	32a	33a
N balance ($kg\ ha^{-1}$)	Log	0.2183	-44a	-54a	-25a	-2a

†Means for treatments within a parameter followed by the same letter are not significantly different according to Tukey's HSD test ($P = 0.05$).

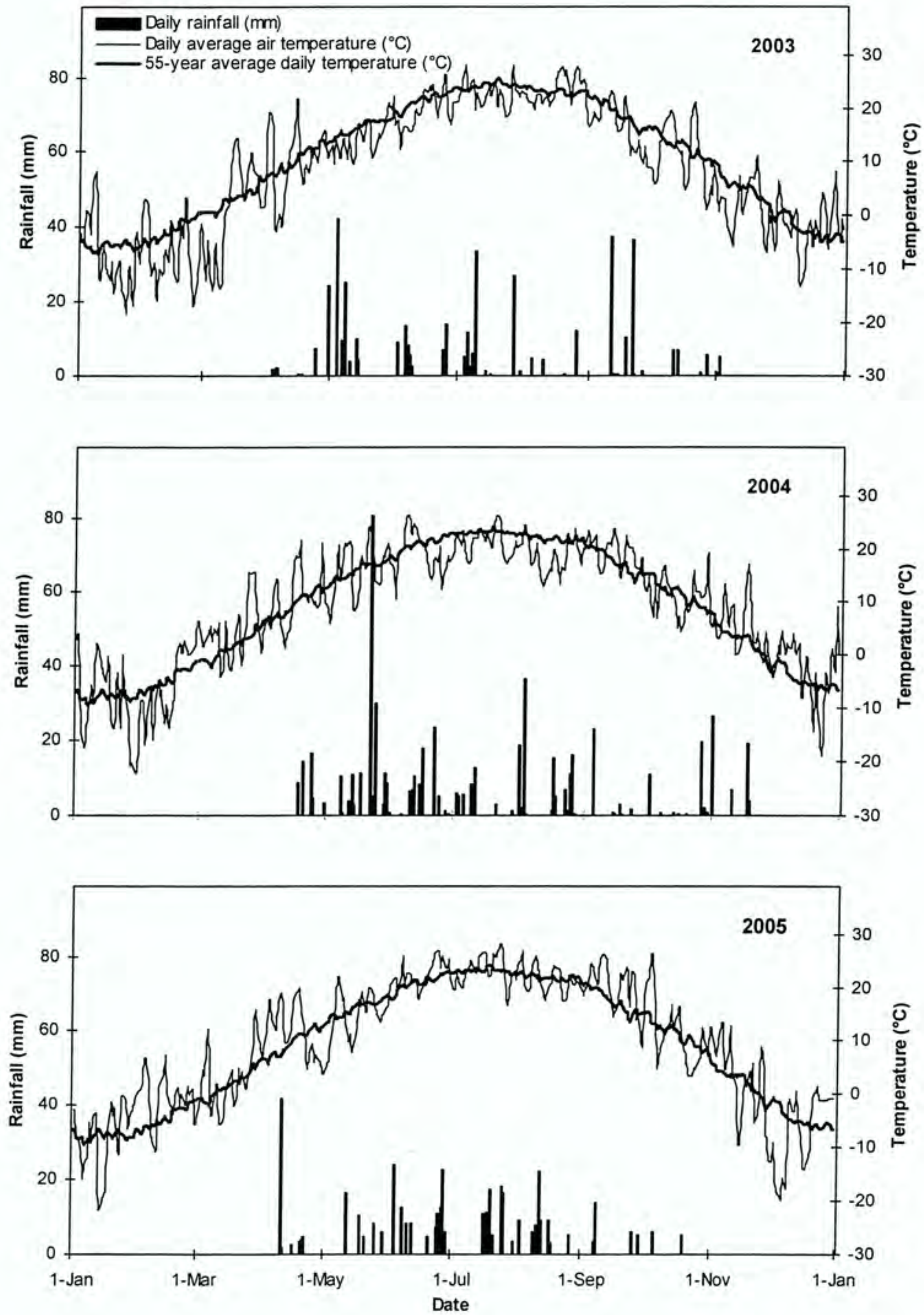

Figure 1. Temperature and rainfall conditions at the Iowa State University Bruner Farm near Ames in 2003, 2004, and 2005.

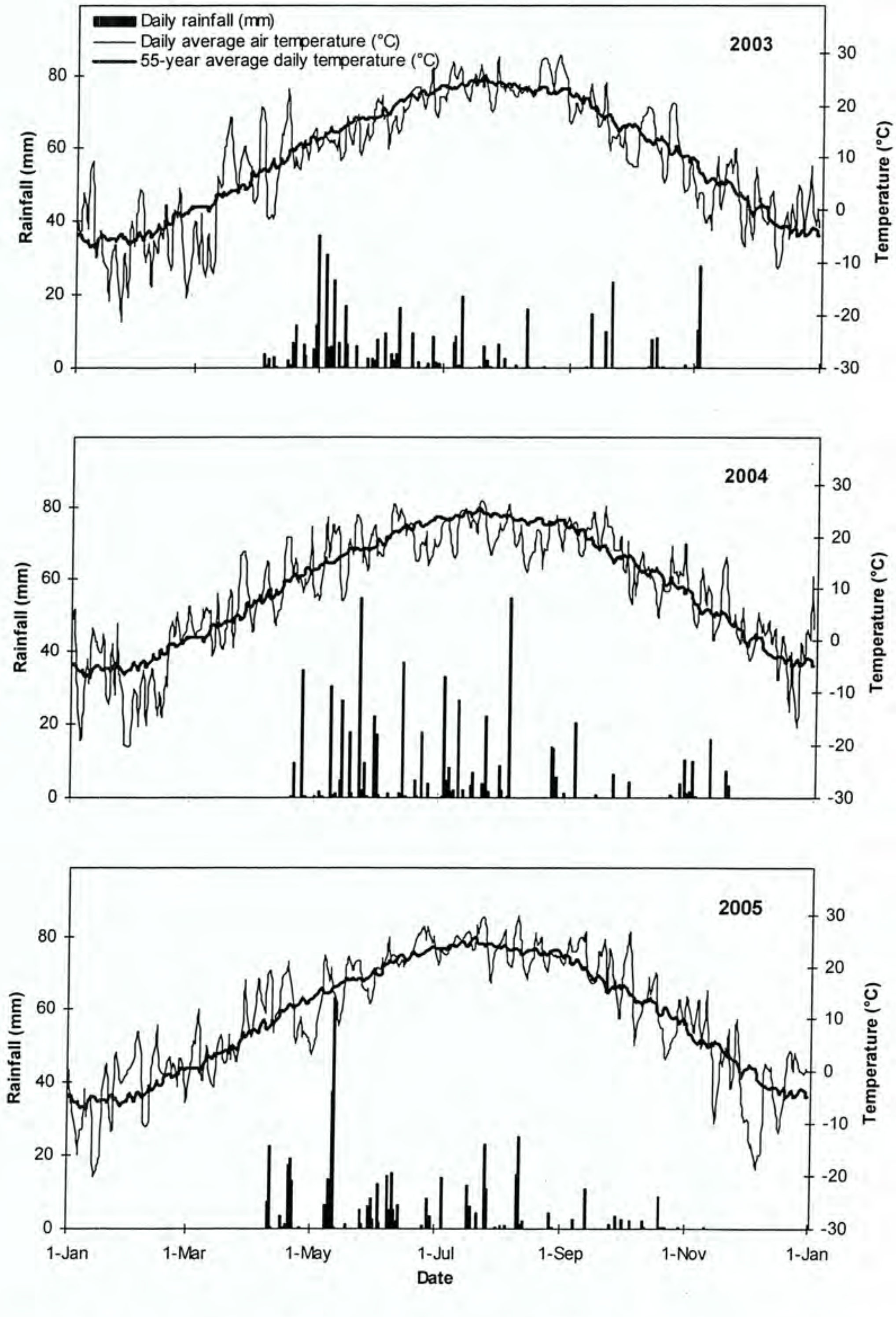

Figure 2. Temperature and rainfall conditions at the Iowa State University Armstrong Farm near Lewis in 2003, 2004, and 2005.

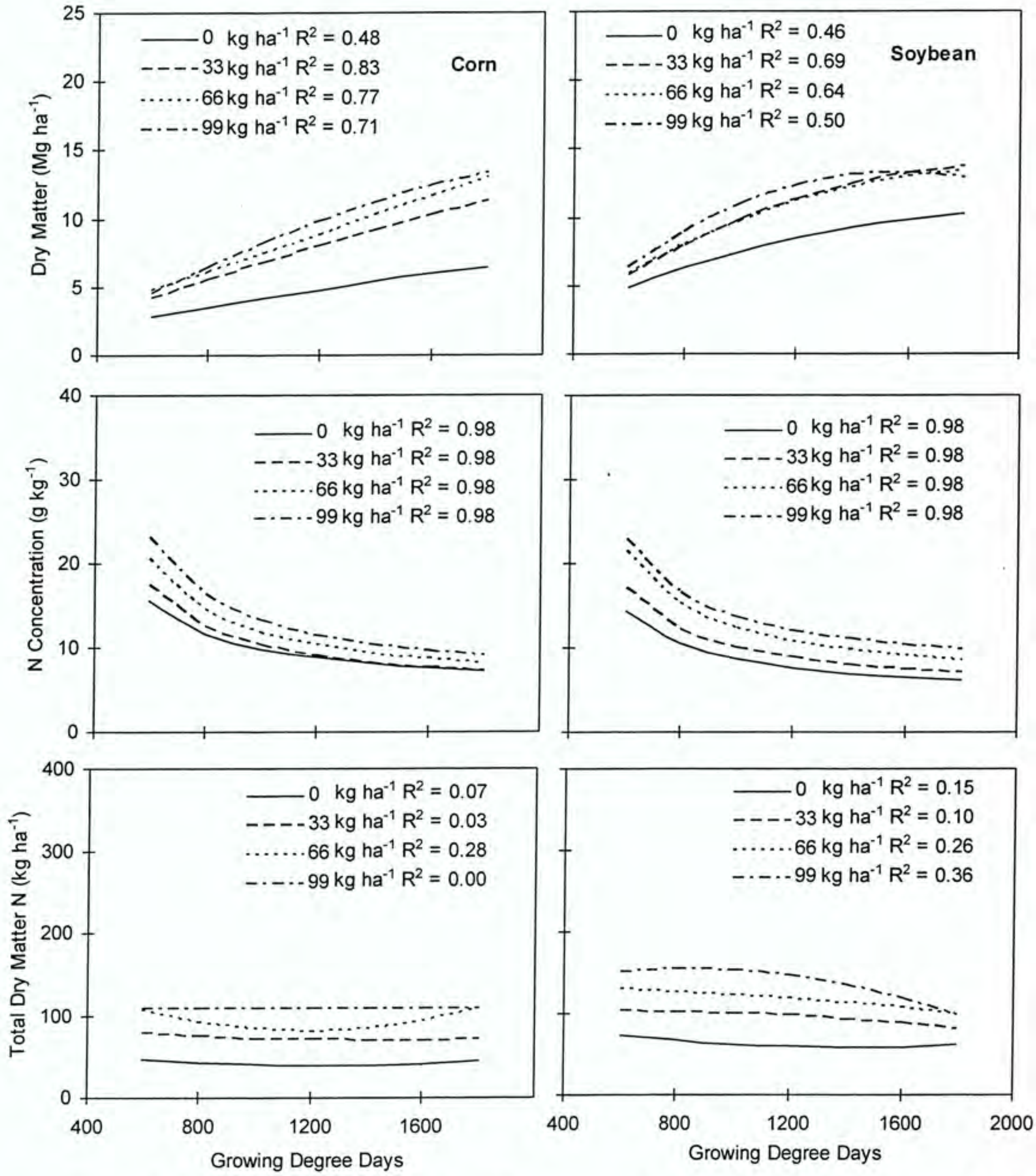

Figure 3. Dry matter accumulation, N concentration, and N uptake curves for winter triticale grown near Ames, Iowa in 2004 and 2005. Growing degree days were calculated from 1 March using a base temperature of 0°C.

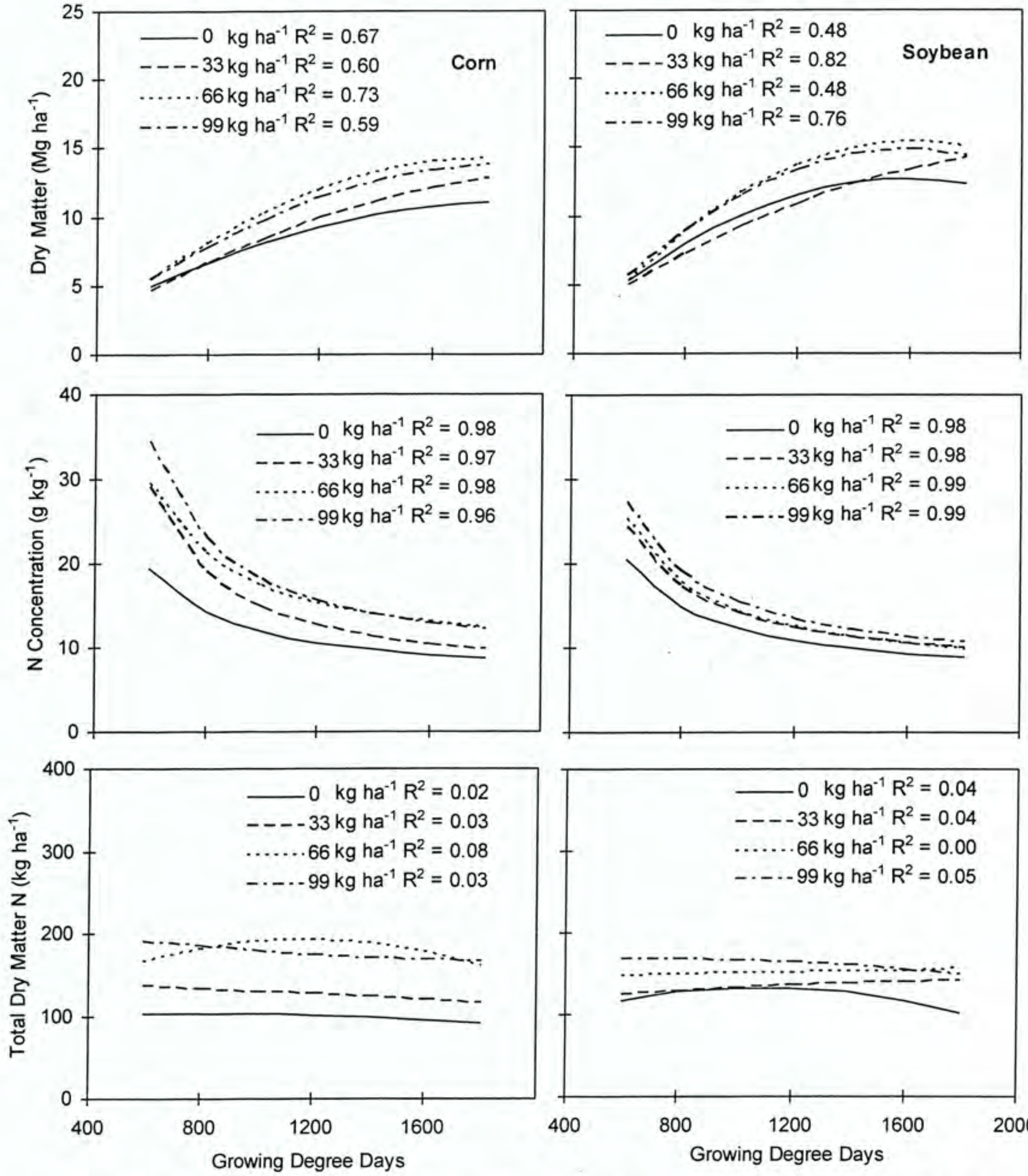

Figure 4. Dry matter accumulation, N concentration, and N uptake curves for winter triticale grown near Lewis, Iowa in 2004 and 2005. Growing degree-days were calculated from 1 March using a base temperature of 0°C.

Chapter 4: General Conclusions

Triticale can be used in many different ways to diversify Iowa crop rotations but there are many questions needing answers. Incorporating triticale into cropping systems may help reduce soil erosion, capture N from previous crops, improve nutrient cycling, provide a hedge against weather extremes, and prevent leaching of nitrate from the soil. Triticale has many potential uses as cover, forage, grain, and straw. It will also diversify the predominant corn and soybean system, thus buffering against weather, disease, insect, or market problems.

Nitrogen is essential for plant growth (Di and Cameron, 2000) and proper N management is required for reducing negative environmental effects associated with N fertilizer additions to cropping systems. Nitrate loss of from fertilizer N in the U.S. Corn and Soybean belt has received partial blame for hypoxia in the Gulf of Mexico (Balkcom et al., 2003).

This research was conducted near Ames and Lewis, Iowa in 2004 and 2005. Four N fertilization rates (0, 33, 66, 99 kg N ha^{-1}) were evaluated in a randomized complete block design in order to quantify N uptake of triticale and to determine the amount of N fertilizer needed to achieve maximum triticale forage and grain yield following either corn (*Zea mays* L.) or soybean (*Glycine max* (L.) Merr.) and to determine and identify the soil NO_3–N status before and after growing winter triticale.

The disease Septoria leaf blotch (*Septoria* spp.) caused seasonal differences in grain yield for winter triticale following either corn or soybean. Triticale dry matter production and grain yield following corn or soybean at Ames showed a significant response to the first increment of N (33 kg ha^{-1}), but no additional response at the 66 or 99 kg N ha^{-1} rates. This suggests that 33 kg N ha^{-1} was sufficient for triticale following corn or soybean in Ames, IA.

There was also a significant N rate response for spikes m^{-2} for triticale following Ames corn and a response for seeds $spike^{-1}$ for triticale following both corn and soybean at Ames between the 33 and 99 kg ha^{-1} N rates. Triticale grain yield following corn and soybean at Ames showed a significant N rate response, but at Lewis there was no change in grain yield as the N rate increased. Following corn and soybean at both Ames and Lewis, triticale test weight and moisture content decreased significantly, compared to the control, at the two higher rates of N application.

Winter triticale grown after either corn silage or soybean as a cover crop, supplemental forage, or grain crop can capture a significant amount of soil NO_3-N. Reductions in NO_3-N to a soil depth of 120 cm from growing triticale were 33 to 53 kg ha^{-1}. Since a triticale crop accumulates the majority of its N before the middle of May, this crop can improve Iowa cropping systems by reducing N loss from the soil during the winter and early-spring months.

It is recommended winter triticale following either corn or soybean can be grown with only 33 kg N ha^{-1} fertilizer to optimize dry matter production and grain yield. Through this research it has been proven that 33 kg N ha^{-1} will provide high triticale yields with minimum nitrate loss when grown following corn or soybean in Iowa.

Appendix: ANOVA Tables

Table 1. ANOVA for year and nitrogen fertilizer effects on grain yield, yield components and quality of winter triticale grown after corn or soybean at Ames and Lewis, IA in 2004 and 2005. Analysis was done using transformations on each variable.

Ames, Corn									
		Grain yield		Spikes m^{-2}		Seeds $spike^{-1}$		Kernel weight	
Source	df	MS (Log Mg ha^{-1})	*P(F)*	MS (Square root no.)	*P(F)*	MS (Square root no.)	*P(F)*	MS (Reciprocal mg)	*P(F)*
Year (Y)	1	2.128	---	241.277	---	5.806	---	5.3×10^{-4}	---
Block (Year)	6	7.1×10^{-2}	---	4.395	---	2.4×10^{-1}	---	3.2×10^{-6}	---
Nitrogen (N)	3	5.2×10^{-2}	0.0163	26.852	0.0053	5.1×10^{-1}	0.0208	2.494	0.6979
Y × N	3	2.5×10^{-2}	0.3157	5.9×10^{-1}	0.9397	2.9×10^{-2}	0.9235	4.8×10^{-6}	0.0374
Residual	18	2.0×10^{-2}	---	4.448	---	1.8×10^{-1}	---	1.4×10^{-6}	---
		Moisture		Test weight		Ergot		Lodging	
		MS (Log g kg^{-1})	*P(F)*	MS (Reciprocal g hL^{-1})	*P(F)*	MS (Log mg kg^{-1})	*P(F)*	MS (Log %)	*P(F)*
Year (Y)	1	7.9×10^{-2}	---	1.370	---	4.5×10^{-3}	---	4.852	---
Block (Year)	6	9.1×10^{-4}	---	7.109	---	6.7×10^{-5}	---	1.253	---
Nitrogen (N)	3	1.3×10^{-3}	0.4358	2.018	0.7476	6.7×10^{-5}	0.5000	1.527	0.1396
Y × N	3	1.1×10^{-3}	0.1985	4.708	<0.001	6.7×10^{-5}	0.3203	3.8×10^{-1}	0.7308
Residual	18	6.1×10^{-4}	---	2.936	---	5.3×10^{-4}	---	8.6×10^{-1}	---

Table 1. (continued)

		Ames, Soybean							
		Grain yield		Spikes m^{-2}		Seeds $spike^{-1}$		Kernel weight	
Source	df	MS (Log Mg ha^{-1})	*P(F)*	MS (Square root no.)	*P(F)*	MS (Square root no.)	*P(F)*	MS (Reciprocal mg)	*P(F)*
Year (Y)	1	1.742	---	493.219	---	2.323	---	3.2×10^{-4}	---
Block (Year)	6	1.6×10^{-2}	---	2.880	---	5.1×10^{-2}	---	6.4×10^{-6}	---
Nitrogen (N)	3	6.8×10^{-2}	0.0440	12.748	0.0712	2.8×10^{-1}	0.0387	2.0×10^{-5}	0.4141
Y × N	3	6.7×10^{-3}	0.2073	1.803	0.6204	2.5×10^{-2}	0.8803	1.5×10^{-5}	0.0606
Residual	18	4.0×10^{-3}	---	2.981	---	1.1×10^{-1}	---	5.1×10^{-6}	---
		Moisture		Test weight		Ergot		Lodging	
		MS (Log g kg^{-1})	*P(F)*	MS (Reciprocal g hL^{-1})	*P(F)*	MS (Log mg kg^{-1})	*P(F)*	MS (Log %)	*P(F)*
Year (Y)	1	1.3×10^{-1}	---	1.161	---	6.2×10^{-3}	---	2.7×10^{-1}	---
Block (Year)	6	2.8×10^{-3}	---	5.685	---	4.1×10^{-3}	---	1.105	---
Nitrogen (N)	3	4.6×10^{-3}	0.4358	2.664	0.6965	3.3×10^{-3}	0.5000	6.261	0.0422
Y × N	3	1.1×10^{-3}	0.1985	5.102	0.0008	3.3×10^{-3}	0.2855	5.9×10^{-1}	0.4230
Residual	18	4.1×10^{-4}	---	5.785	---	2.4×10^{-3}	---	6.0×10^{-1}	---

Table 1. (continued)

		Lewis, Corn							
		Grain yield		Spikes m^{-2}		Seeds $spike^{-1}$		Kernel weight	
Source	df	MS (Log Mg ha^{-1})	*P(F)*	MS (Square root no.)	*P(F)*	MS (Square root no.)	*P(F)*	MS (Reciprocal mg)	*P(F)*
Year (Y)	1	4.1×10^{-1}	---	100.182	---	3.063	---	3.5×10^{-4}	---
Block (Year)	6	9.9×10^{-2}	---	3.448	---	5.5×10^{-2}	---	2.7×10^{-5}	---
Nitrogen (N)	3	2.8×10^{-2}	0.1199	19.533	0.1888	2.9×10^{-2}	0.5170	3.7×10^{-5}	0.4871
Y × N	3	5.9×10^{-3}	0.9028	6.300	0.1939	3.1×10^{-2}	0.9102	3.6×10^{-5}	0.2142
Residual	18	3.2×10^{-2}	---	3.613	---	1.7×10^{-1}	---	2.2×10^{-5}	---
		Moisture		Test weight		Ergot		Lodging	
		MS (Log g kg^{-1})	*P(F)*	MS (Reciprocal g hL^{-1})	*P(F)*	MS (Log mg kg^{-1})	*P(F)*	MS (Log %)	*P(F)*
Year (Y)	1	1.2×10^{-1}	---	3.789	---	4.3×10^{-6}	---	18.170	---
Block (Year)	6	5.9×10^{-4}	---	6.235	---	1.4×10^{-4}	---	2.301	---
Nitrogen (N)	3	2.1×10^{-3}	0.0397	8.466	0.0675	7.1×10^{-5}	0.7406	2.568	0.1354
Y × N	3	1.9×10^{-4}	0.8408	1.148	0.6242	1.6×10^{-4}	0.6107	6.1×10^{-1}	0.7030
Residual	18	6.7×10^{-4}	---	1.918	---	2.6×10^{-4}	---	1.291	---

Table 1. (continued)

		Lewis, Soybean							
		Grain yield		Spikes m^{-2}		Seeds $spike^{-1}$		Kernel weight	
Source	df	MS (Log Mg ha^{-1})	*P(F)*	MS (Square root no.)	*P(F)*	MS (Square root no.)	*P(F)*	MS (Reciprocal mg)	*P(F)*
Year (Y)	1	1.4×10^{-1}	---	594.565	---	3.188	---	8.3×10^{-5}	---
Block (Year)	6	1.1×10^{-1}	---	9.340	---	6.8×10^{-2}	---	1.2×10^{-5}	---
Nitrogen (N)	3	7.5×10^{-2}	0.5203	6.000	0.5729	2.4×10^{-1}	0.5729	5.2×10^{-5}	0.4719
Y × N	3	8.0×10^{-2}	0.0489	7.556	0.2409	5.9×10^{-2}	0.2409	4.8×10^{-5}	0.1284
Residual	18	2.5×10^{-2}	---	4.938	---	1.6×10^{-1}	---	2.2×10^{-5}	---
		Moisture		Test weight		Ergot		Lodging	
		MS (Log g kg^{-1})	*P(F)*	MS (Reciprocal g hL^{-1})	*P(F)*	MS (Log mg kg^{-1})	*P(F)*	MS (Log %)	*P(F)*
Year (Y)	1	2.3×10^{-1}	---	8.840	---	6.6×10^{-4}	---	3.753	---
Block (Year)	6	1.1×10^{-3}	---	1.616	---	1.6×10^{-4}	---	2.084	---
Nitrogen (N)	3	6.1×10^{-3}	0.1505	1.140	0.0333	4.7×10^{-5}	0.7739	3.814	0.2912
Y × N	3	1.6×10^{-3}	0.1662	9.081	0.7727	1.2×10^{-4}	0.7770	1.903	0.2947
Residual	18	8.5×10^{-4}	---	2.427	---	3.3×10^{-4}	---	1.427	---

Table 2. ANOVA for year and nitrogen fertilizer effects on dry matter and plant N status of winter triticale grown after corn or soybean at Ames and Lewis, IA in 2004 and 2005. Analysis was done using transformations on the dependent variable.

		Ames, Corn					
		Fall dry matter		Plant N – Fall		Plant N – Fall	
Source	df	MS (Reciprocal square root Mg ha^{-1})	*P(F)*	MS (g kg^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*
Year (Y)	1	22.105	---	8.1×10^{1}	---	24.074	---
Block (Year)	6	1.5×10^{-1}	---	18.730	---	9.3×10^{-2}	---
Nitrogen (N)	3	5.5×10^{-2}	0.5644	8.398	0.3380	2.3×10^{-2}	0.5725
Y × N	3	6.8×10^{-2}	0.7670	4.960	0.6654	2.9×10^{-2}	0.8223
Residual	18	1.8×10^{-1}	---	9.304	---	9.4×10^{-2}	---
		Straw N		Grain N		Grain N	
		MS (Square root g kg^{-1})	*P(F)*	MS (Reciprocal square root g kg^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*
Year (Y)	1	1.7×10^{-2}	---	4.3×10^{-3}	---	1.100	---
Block (Year)	6	1.8×10^{-1}	---	4.2×10^{-5}	---	1.0×10^{-2}	---
Nitrogen (N)	3	1.7×10^{-1}	0.2367	6.7×10^{-4}	0.3771	1.8×10^{-1}	0.3854
Y × N	3	6.7×10^{-2}	0.0291	4.5×10^{-4}	0.0739	1.3×10^{-1}	0.0461
Residual	18	1.8×10^{-2}	---	1.7×10^{-4}	---	3.9×10^{-1}	---

Table 2. (continued)

		Ames, Soybean					
		Fall dry matter		Plant N – Fall		Plant N – Fall	
Source	df	MS (Reciprocal square root Mg ha^{-1})	*P(F)*	MS (g kg^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*
Year (Y)	1	4.482	---	91.801	---	10.302	---
Block (Year)	6	1.3×10^{-2}	---	5.925	---	1.9×10^{-2}	---
Nitrogen (N)	3	3.1×10^{-2}	0.4201	11.287	0.2234	2.8×10^{-2}	0.4785
Y × N	3	2.4×10^{-2}	0.4680	4.279	0.8564	2.6×10^{-2}	0.4629
Residual	18	2.8×10^{-2}	---	16.743	---	2.9×10^{-2}	---
		Straw N		Grain N		Grain N	
		MS (Square root g kg^{-1})	*P(F)*	MS (Reciprocal square root g kg^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*
Year (Y)	1	5.0×10^{-1}	---	2.0×10^{-3}	---	5.3×10^{-1}	---
Block (Year)	6	1.4×10^{-1}	---	3.6×10^{-5}	---	9.5×10^{-3}	---
Nitrogen (N)	3	2.5×10^{-1}	0.0319	1.5×10^{-3}	0.0858	3.9×10^{-1}	0.0877
Y × N	3	1.9×10^{-2}	0.4024	2.4×10^{-4}	0.2645	6.4×10^{-2}	0.2396
Residual	18	1.8×10^{-2}	---	1.7×10^{-4}	---	4.2×10^{-2}	---

Table 2. (continued)

		Lewis, Corn					
		Fall dry matter		Plant N – Fall		Plant N – Fall	
Source	df	MS (Reciprocal square root Mg ha^{-1})	*P(F)*	MS (g kg^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*
Year (Y)	1	4.403	---	96.953	---	10.706	---
Block (Year)	6	4.3×10^{-2}	---	8.830	---	6.4×10^{-2}	---
Nitrogen (N)	3	2.3×10^{-2}	0.5527	5.019	0.7368	1.3×10^{-2}	0.9134
Y × N	3	2.7×10^{-2}	0.0653	11.211	0.5424	8.1×10^{-2}	0.0255
Residual	18	9.4×10^{-3}	---	15.166	---	2.1×10^{-2}	---
		Straw N		Grain N		Grain N	
		MS (Square root g kg^{-1})	*P(F)*	MS (Reciprocal square root g kg^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*
Year (Y)	1	1.2×10^{-2}	---	3.1×10^{-3}	---	9.2×10^{-1}	---
Block (Year)	6	1.2×10^{-1}	---	9.5×10^{-5}	---	3.0×10^{-2}	---
Nitrogen (N)	3	5.0×10^{-1}	0.0371	1.8×10^{-4}	0.0983	5.4×10^{-2}	0.1194
Y × N	3	4.3×10^{-2}	0.5939	3.3×10^{-5}	0.9087	1.2×10^{-2}	0.8827
Residual	18	6.7×10^{-2}	---	1.8×10^{-4}	---	5.3×10^{-2}	---

Table 2. (continued)

		Lewis, Soybean					
		Fall dry matter		Plant N – Fall		Plant N – Fall	
Source	df	MS (Reciprocal square root Mg ha^{-1})	*P(F)*	MS (g kg^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*
Year (Y)	1	3.592	---	215.800	---	10.512	---
Block (Year)	6	1.4 x 10^{-2}	---	7.430	---	3.6 x 10^{-2}	---
Nitrogen (N)	3	1.5 x 10^{-2}	0.3160	2.619	0.9448	2.2 x 10^{-2}	0.5122
Y × N	3	8.4 x 10^{-3}	0.6126	22.526	0.1015	2.2 x 10^{-2}	0.4578
Residual	18	1.4 x 10^{-2}	---	9.383	---	2.5 x 10^{-2}	---
		Straw N		Grain N		Grain N	
		MS (Square root g kg^{-1})	*P(F)*	MS (Reciprocal square root g kg^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*
Year (Y)	1	1.298	---	5.3 x 10^{-4}	---	1.8 x 10^{-1}	---
Block (Year)	6	5.5 x 10^{-2}	---	4.6 x 10^{-5}	---	1.5 x 10^{-2}	---
Nitrogen (N)	3	1.9 x 10^{-1}	0.0473	4.6 x 10^{-4}	0.3195	1.4 x 10^{-1}	0.3133
Y × N	3	2.0 x 10^{-2}	0.8522	2.5 x 10^{-4}	0.2123	7.5 x 10^{-2}	0.2159
Residual	18	7.6 x 10^{-2}	---	1.5 x 10^{-4}	---	4.6 x 10^{-2}	---

Table 3. ANOVA for year and nitrogen fertilizer effects on soil nitrate status for winter triticale grown after corn or soybean at Ames and Lewis, IA in 2004 and 2005. Analysis was done using transformations on the dependent variable.

	Fall Soil NO_3-N			Summer Soil NO_3-N			ΔNO_3-N		
Source	df	MS (Log kg ha^{-1})	*P(F)*	df	MS (Log (kg ha^{-1} +1))	*P(F)*	df	MS (Reciprocal (kg ha^{-1} + 100))	*P(F)*
					Ames, Corn, 0 to 15 cm				
Year (Y)	1	3.366	---	1	1.463	---	1	3.6×10^{-5}	---
Block (Year)	6	5.8×10^{-2}	---	6	1.5×10^{-1}	---	6	2.6×10^{-6}	---
Nitrogen (N)	3	2.7×10^{-2}	0.5446	3	3.7×10^{-2}	0.7801	3	1.132	0.1774
Y × N	3	3.1×10^{-2}	0.6153	3	9.8×10^{-2}	0.2203	3	3.4×10^{-7}	0.8425
Residual	18	5.1×10^{-2}	---	18	6.0×10^{-2}	---	18	1.3×10^{-6}	---
					Ames, Corn, 15 to 30 cm				
Year (Y)	1	5.3×10^{-1}	---	1	6.4×10^{-4}	---	1	5.393	---
Block (Year)	6	4.4×10^{-1}	---	6	2.2×10^{-1}	---	6	3.063	---
Nitrogen (N)	3	1.1×10^{-1}	0.4768	3	3.5×10^{-2}	0.5978	3	2.213	0.3499
Y × N	3	1.1×10^{-1}	0.7272	3	4.7×10^{-2}	0.7462	3	1.362	0.6155
Residual	18	2.4×10^{-1}	---	18	1.1×10^{-1}	---	18	2.223	---

Table 3. (continued)

	Fall Soil NO_3-N			Summer Soil NO_3-N			ΔNO_3-N		
Source	df	MS (Log kg ha^{-1})	*P(F)*	df	MS (Log (kg ha^{-1} +1))	*P(F)*	df	MS (Reciprocal (kg ha^{-1} + 100))	*P(F)*
					Ames, Corn, 30 to 60 cm				
Year (Y)	1	2.413	---	1	1.415	---	1	1.198	---
Block (Year)	6	1.9×10^{-1}	---	6	1.9×10^{-1}	---	6	7.190	---
Nitrogen (N)	3	5.6×10^{-2}	0.7201	3	1.6×10^{-1}	0.6800	3	2.882	0.5555
Y × N	3	1.2×10^{-1}	0.4805	3	3.0×10^{-1}	0.3782	3	3.434	0.2081
Residual	18	1.4×10^{-1}	---	18	2.7×10^{-1}	---	18	2.051	---
					Ames, Corn, 60 to 90 cm				
Year (Y)	1	1.877	---	1	1.3×10^{-3}	---	1	1.536	---
Block (Year)	6	5.0×10^{-2}	---	6	1.8×10^{-1}	---	6	1.583	---
Nitrogen (N)	3	1.1×10^{-1}	0.4180	3	2.1×10^{-1}	0.6848	3	1.827	0.3613
Y × N	3	8.2×10^{-2}	0.6646	3	3.8×10^{-1}	0.2327	3	1.169	0.8154
Residual	18	1.5×10^{-1}	---	18	2.4×10^{-1}	---	18	3.728	---

Table 3. (continued)

	Fall Soil NO_3-N			Summer Soil NO_3-N			ΔNO_3-N		
Source	df	MS (Log kg ha^{-1})	*P(F)*	df	MS (Log (kg ha^{-1} +1))	*P(F)*	df	MS (Reciprocal (kg ha^{-1} + 100))	*P(F)*
Ames, Corn, 90 to 120 cm									
Year (Y)	1	2.422	---	1	9.1×10^{-1}	---	1	1.762	---
Block (Year)	6	1.1×10^{-1}	---	6	6.6×10^{-2}	---	6	1.722	---
Nitrogen (N)	3	3.9×10^{-1}	0.0823	3	4.8×10^{-1}	0.4390	3	2.209	0.9312
Y × N	3	6.2×10^{-2}	0.9350	3	4.0×10^{-1}	0.1320	3	1.604	0.6911
Residual	18	4.5×10^{-1}	---	15	1.8×10^{-1}	---	15	3.239	---
Ames, Soybean, 0 to 15 cm									
Year (Y)	1	7.3×10^{-2}	---	1	8.4×10^{-1}	---	1	1.7×10^{-6}	---
Block (Year)	6	5.8×10^{-2}	---	6	2.0×10^{-1}	---	6	3.2×10^{-6}	---
Nitrogen (N)	3	5.3×10^{-3}	0.1755	3	5.6×10^{-1}	0.1728	3	1.280	0.2480
Y × N	3	1.6×10^{-3}	0.9901	3	1.7×10^{-1}	0.6555	3	5.4×10^{-7}	0.8637
Residual	18	4.3×10^{-2}	---	18	3.0×10^{-1}	---	18	2.2×10^{-6}	---

Table 3. (continued)

	Fall Soil NO_3-N			Summer Soil NO_3-N			ΔNO_3-N		
Source	df	MS (Log kg ha^{-1})	*P(F)*	df	MS (Log (kg ha^{-1} +1))	*P(F)*	df	MS (Reciprocal (kg ha^{-1} + 100))	*P(F)*
				Ames, Soybean, 15 to 30 cm					
Year (Y)	1	4.9×10^{-2}	---	1	5.4×10^{-3}	---	1	4.379	---
Block (Year)	6	1.4×10^{-1}	---	6	2.2×10^{-1}	---	6	4.007	---
Nitrogen (N)	3	6.7×10^{-2}	0.6288	3	3.1×10^{-2}	0.5179	3	2.134	0.3432
Y × N	3	1.0×10^{-1}	0.4238	3	3.3×10^{-2}	0.5410	3	1.284	0.6523
Residual	18	1.0×10^{-1}	---	18	4.5×10^{-2}	---	18	2.319	---
				Ames, Soybean, 30 to 60 cm					
Year (Y)	1	1.550	---	1	3.5×10^{-1}	---	1	1.932	---
Block (Year)	6	2.8×10^{-1}	---	6	2.4×10^{-1}	---	6	2.661	---
Nitrogen (N)	3	1.5×10^{-1}	0.3807	3	6.8×10^{-2}	0.3080	3	2.054	0.1363
Y × N	3	1.0×10^{-1}	0.2938	3	3.6×10^{-2}	0.8344	3	4.943	0.7865
Residual	18	7.6×10^{-2}	---	18	1.3×10^{-1}	---	18	1.395	---

Table 3. (continued)

	Fall Soil NO_3-N			Summer Soil NO_3-N			ΔNO_3-N		
Source	df	MS (Log kg ha^{-1})	*P(F)*	df	MS (Log (kg ha^{-1} +1))	*P(F)*	df	MS (Reciprocal (kg ha^{-1} + 100))	*P(F)*
				Ames, Soybean, 60 to 90 cm					
Year (Y)	1	2.2×10^{-1}	---	1	1.9×10^{-3}	---	1	5.161	---
Block (Year)	6	9.6×10^{-2}	---	6	1.6×10^{-1}	---	6	2.823	---
Nitrogen (N)	3	1.8×10^{-1}	0.0563	3	5.8×10^{-1}	0.3832	3	1.292	0.1328
Y × N	3	2.1×10^{-2}	0.8056	3	4.0×10^{-1}	0.1024	3	3.039	0.5094
Residual	18	6.3×10^{-2}	---	17	1.7×10^{-1}	---	17	3.786	---
				Ames, Soybean, 90 to 120 cm					
Year (Y)	1	3.2×10^{-1}	---	1	1.4×10^{-3}	---	1	4.493	---
Block (Year)	6	1.7×10^{-1}	---	6	1.4×10^{-1}	---	6	7.885	---
Nitrogen (N)	3	2.0×10^{-1}	0.1416	3	2.5×10^{-1}	0.2923	3	1.801	0.8543
Y × N	3	5.1×10^{-2}	0.8126	3	1.3×10^{-1}	0.5560	3	7.060	0.1394
Residual	18	1.6×10^{-1}	---	16	1.8×10^{-1}	---	16	3.349	---

Table 3. (continued)

	Fall Soil NO_3-N			Summer Soil NO_3-N			ΔNO_3-N		
Source	df	MS (Log kg ha^{-1})	*P(F)*	df	MS (Log (kg ha^{-1} +1))	*P(F)*	df	MS (Reciprocal (kg ha^{-1} + 100))	*P(F)*
					Lewis, Corn, 0 to 15 cm				
Year (Y)	1	7.248	---	1	1.459	---	1	5.2×10^{-4}	---
Block (Year)	6	3.0×10^{-2}	---	6	1.6×10^{-1}	---	6	3.1×10^{-5}	---
Nitrogen (N)	3	1.5×10^{-1}	0.1946	3	1.4×10^{-1}	0.3342	3	3.7×10^{-5}	0.4127
Y × N	3	5.0×10^{-2}	0.6285	3	8.4 x 10-2	0.5457	3	2.8×10^{-5}	0.5102
Residual	18	8.5×10^{-2}	---	18	1.1×10^{-1}	---	18	3.5×10^{-5}	---
					Lewis, Corn, 15 to 30 cm				
Year (Y)	1	2.677	---	1	3.396	---	1	8.055	---
Block (Year)	6	8.9×10^{-2}	---	6	6.1×10^{-2}	---	6	1.065	---
Nitrogen (N)	3	8.1×10^{-2}	0.6424	3	4.1×10^{-1}	0.0361	3	1.175	0.5719
Y × N	3	1.3×10^{-1}	0.2965	3	3.5×10^{-2}	0.8660	3	1.475	0.4367
Residual	18	9.6×10^{-2}	---	18	1.4×10^{-1}	---	18	1.550	---

Table 3. (continued)

	Fall Soil NO_3-N			Summer Soil NO_3-N			ΔNO_3-N		
Source	df	MS (Log kg ha^{-1})	*P(F)*	df	MS (Log (kg ha^{-1} +1))	*P(F)*	df	MS (Reciprocal (kg ha^{-1} + 100))	*P(F)*
				Lewis, Corn, 30 to 60 cm					
Year (Y)	1	6.808	---	1	3.800	---	1	8.782	---
Block (Year)	6	1.1×10^{-1}	---	6	2.3×10^{-1}	---	6	9.803	---
Nitrogen (N)	3	3.1×10^{-2}	0.6984	3	8.0×10^{-2}	0.8839	3	2.682	0.9242
Y × N	3	5.9×10^{-2}	0.4419	3	3.8×10^{-1}	0.2082	3	1.806	0.5252
Residual	18	6.3×10^{-2}	---	17	2.3×10^{-1}	---	17	2.338	---
				Lewis, Corn, 60 to 90 cm					
Year (Y)	1	11.148	---	1	4.5×10^{-2}	---	1	4.599	---
Block (Year)	6	2.6×10^{-1}	---	6	9.0×10^{-2}	---	6	1.598	---
Nitrogen (N)	3	8.3×10^{-2}	0.1861	3	3.2×10^{-1}	0.5511	3	2.968	0.3478
Y × N	3	2.6×10^{-2}	0.8087	3	3.8×10^{-1}	0.2312	3	1.813	0.8246
Residual	18	8.2×10^{-2}	---	15	2.4×10^{-1}	---	15	6.036	---

Table 3. (continued)

	Fall Soil NO_3-N			Summer Soil NO_3-N			ΔNO_3-N		
Source	df	MS (Log kg ha^{-1})	*P(F)*	df	MS (Log (kg ha^{-1}+1))	*P(F)*	df	MS (Reciprocal (kg ha^{-1} + 100))	*P(F)*
Lewis, Corn, 90 to 120 cm									
Year (Y)	1	7.781	---	1	1.700	---	1	1.604	---
Block (Year)	6	1.6×10^{-1}	---	6	1.1×10^{-1}	---	6	5.357	---
Nitrogen (N)	3	9.9×10^{-2}	0.6737	3	1.149	0.0431	3	1.030	0.2995
Y × N	3	3.7×10^{-2}	0.8974	3	1.1×10^{-1}	0.4721	3	5.300	0.3056
Residual	17	1.9×10^{-1}	---	13	1.2×10^{-1}	---	12	3.935	---
Lewis, Soybean, 0 to 15 cm									
Year (Y)	1	3.259	---	1	7.2×10^{-2}	---	1	3.0×10^{-4}	---
Block (Year)	6	6.4×10^{-2}	---	6	5.3×10^{-2}	---	6	2.0×10^{-6}	---
Nitrogen (N)	3	1.4×10^{-1}	0.1046	3	3.0×10^{-1}	0.0905	3	1.6×10^{-5}	0.5556
Y × N	3	2.7×10^{-2}	0.6431	3	5.1×10^{-1}	0.4184	3	2.0×10^{-5}	0.0409
Residual	18	4.8×10^{-2}	---	18	5.1×10^{-2}	---	18	5.8×10^{-6}	---

Table 3. (continued)

Source	df	Fall Soil NO_3-N MS (Log kg ha^{-1})	$P(F)$	df	Summer Soil NO_3-N MS (Log (kg ha^{-1}+1))	$P(F)$	df	ΔNO_3-N MS (Reciprocal (kg ha^{-1} + 100))	$P(F)$
Lewis, Soybean, 15 to 30cm									
Year (Y)	1	2.6×10^{-1}	---	1	7.8×10^{-1}	---	1	2.179	---
Block (Year)	6	1.0×10^{-1}	---	6	1.8×10^{-1}	---	6	2.220	---
Nitrogen (N)	3	2.7×10^{-1}	0.2852	3	6.1×10^{-1}	0.1422	3	2.787	0.8053
Y × N	3	1.3×10^{-1}	0.1446	3	1.5×10^{-1}	0.3037	3	8.394	0.0196
Residual	18	6.4×10^{-2}	---	18	1.2×10^{-1}	---	18	1.976	---
Lewis, Soybean, 30 to 60 cm									
Year (Y)	1	3.7×10^{-1}	---	1	5.2×10^{-1}	---	1	4.953	---
Block (Year)	6	6.1×10^{-2}	---	6	2.3×10^{-1}	---	6	1.748	---
Nitrogen (N)	3	1.5×10^{-1}	0.4268	3	1.182	0.0688	3	4.081	0.5669
Y × N	3	1.2×10^{-1}	0.4527	3	1.6×10^{-1}	0.5874	3	5.042	0.3379
Residual	18	1.3×10^{-1}	---	18	2.5×10^{-1}	---	18	4.2×10^{-7}	---

Table 3. (continued)

	Fall Soil NO_3-N			Summer Soil NO_3-N			ΔNO_3-N		
Source	df	MS (Log kg ha^{-1})	*P(F)*	df	MS (Log (kg ha^{-1} +1))	*P(F)*	df	MS (Reciprocal (kg ha^{-1} + 100))	*P(F)*
					Lewis, Soybean, 60 to 90 cm				
Year (Y)	1	1.119	---	1	2.437	---	1	2.973	---
Block (Year)	6	1.3×10^{-1}	---	6	9.6×10^{-2}	---	6	1.000	---
Nitrogen (N)	3	2.1×10^{-1}	0.2767	3	1.109	0.0579	3	5.585	0.4904
Y × N	3	1.0×10^{-1}	0.5909	3	1.3×10^{-1}	0.4054	3	5.418	0.2309
Residual	18	1.5×10^{-1}	---	17	1.3×10^{-1}	---	17	3.429	---
					Lewis, Soybean, 90 to 120 cm				
Year (Y)	1	2.449	---	1	5.434	---	1	1.412	---
Block (Year)	6	4.3×10^{-2}	---	6	1.4×10^{-1}	---	6	4.324	---
Nitrogen (N)	3	1.6×10^{-1}	0.5349	3	9.5×10^{-1}	0.1919	3	1.910	0.1836
Y × N	3	1.8×10^{-1}	0.3267	3	3.1×10^{-1}	0.2717	3	6.001	0.1780
Residual	14	1.4×10^{-1}	---	15	2.2×10^{-1}	---	13	3.144	---

Table 4. ANOVA for year and nitrogen fertilizer effects on fall soil NO_3-N, plant N uptake, summer soil NO_3-N, and estimated N loss from winter triticale grown after corn or soybean at Ames and Lewis, IA in 2004 and 2005. Analysis was done using transformations on each variable.

		Pre Plant Soil NO_3-N		Plant N Uptake		Post Harvest Soil NO_3-N		Estimated N Loss	
Source	df	MS (Log kg ha^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*
Ames, Corn									
Year (Y)	1	2.334	---	4.4×10^{-1}	---	5.6×10^{-1}	---	4.6×10^{-3}	---
Block (Year)	6	4.7×10^{-2}	---	3.2×10^{-2}	---	1.7×10^{-1}	---	1.6×10^{-2}	---
Nitrogen (N)	3	1.1×10^{-2}	0.2492	1.510	0.0203	4.9×10^{-2}	0.7593	3.4×10^{-2}	0.2864
Y × N	3	4.5×10^{-3}	0.9698	8.4×10^{-2}	0.2298	1.2×10^{-1}	0.2648	1.7×10^{-2}	0.4012
Residual	18	5.6×10^{-2}	---	5.3×10^{-2}	---	8.4×10^{-2}	---	1.6×10^{-2}	---
Ames, Soybean									
Year (Y)	1	9.3×10^{-2}	---	1.1×10^{-1}	---	4.8×10^{-1}	---	1.1×10^{-2}	---
Block (Year)	6	4.2×10^{-2}	---	5.2×10^{-2}	---	6.4×10^{-2}	---	2.0×10^{-2}	---
Nitrogen (N)	3	1.5×10^{-2}	0.2647	5.7×10^{-1}	0.0018	3.1×10^{-1}	0.0834	5.4×10^{-2}	0.0024
Y × N	3	6.7×10^{-3}	0.9082	6.0×10^{-3}	0.9615	4.9×10^{-2}	0.7082	7.0 x 10-4	0.9827
Residual	18	3.7×10^{-2}	---	6.3×10^{-2}	---	1.1×10^{-1}	---	1.3×10^{-2}	---

Table 4. (continued)

Source	df	Pre Plant Soil NO_3-N		Plant N Uptake		Post Harvest Soil NO_3-N		Estimated N Loss	
		MS (Log kg ha^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*	MS (Log kg ha^{-1})	*P(F)*
				Lewis, Corn					
Year (Y)	1	7.630	---	1.439	---	2.679	---	9.2×10^{-3}	---
Block (Year)	6	1.6×10^{-2}	---	3.0×10^{-2}	---	7.3×10^{-2}	---	2.7×10^{-2}	---
Nitrogen (N)	3	6.2×10^{-2}	0.3628	7.3×10^{-1}	0.1458	2.2×10^{-1}	0.3863	8.2×10^{-2}	0.5174
Y × N	3	4.0×10^{-2}	0.5116	1.9×10^{-1}	0.0621	1.6×10^{-1}	0.2809	8.7×10^{-2}	0.4238
Residual	18	5.0×10^{-2}	---	6.4×10^{-2}	---	1.1×10^{-1}	---	8.9×10^{-2}	---
				Lewis, Soybean					
Year (Y)	1	1.375	---	5.3×10^{-1}	---	1.2×10^{-1}	---	1.404	---
Block (Year)	6	4.1×10^{-2}	---	2.6×10^{-2}	---	4.1×10^{-2}	---	6.4×10^{-2}	---
Nitrogen (N)	3	1.3×10^{-1}	0.1729	4.2×10^{-1}	0.0574	5.2×10^{-1}	0.0898	1.6×10^{-1}	0.2183
Y × N	3	3.8×10^{-2}	0.3920	5.0×10^{-2}	0.2860	8.8×10^{-2}	0.2474	5.8×10^{-2}	0.6547
Residual	18	3.6×10^{-2}	---	3.7×10^{-2}	---	5.9×10^{-2}	---	1.1×10^{-1}	---

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